DOPPLER RADAR OBSERVATIONS AND ENSEMBLE-BASED DATA ASSIMILATION FOR CLOUD-RESOLVING HURRICANE PREDICTION

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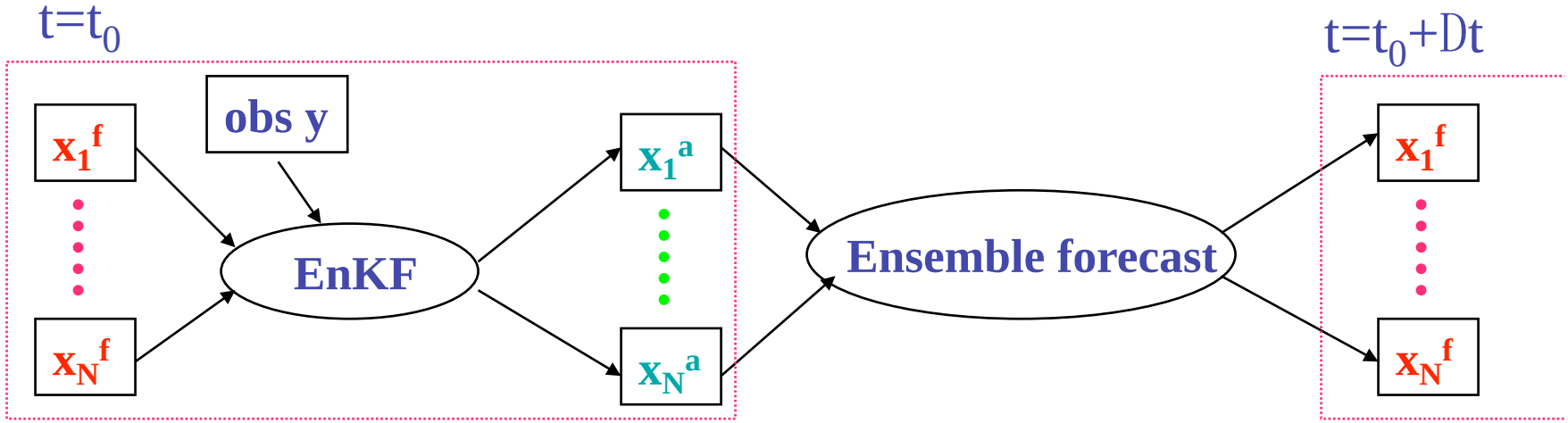
Ensemble Kalman Filter for Mesoscales

(Evensen 1994 JGR; Zhang and Snyder 2007 BAMS)

$$\mathbf{x}^a = \mathbf{x}^f + \mathbf{B}\mathbf{H}^T(\mathbf{H}\mathbf{B}\mathbf{H}^T+\mathbf{R})^{-1}(\mathbf{y}-\mathbf{H}\mathbf{x}^f)$$



Ensemble forecast provides better, flow-dependent estimate of background error covariance: $B = N_e^{-1}\Sigma (x_i^f - \underline{x})(x_i^f - \underline{x})^T$

Equivalence to 4Dvar in linear systems; no adjoint or TLM; fully coupled with ensemble forecast; nonlinear dynamics included; adaptable to be coupled/hybrid with 3D/4DVar

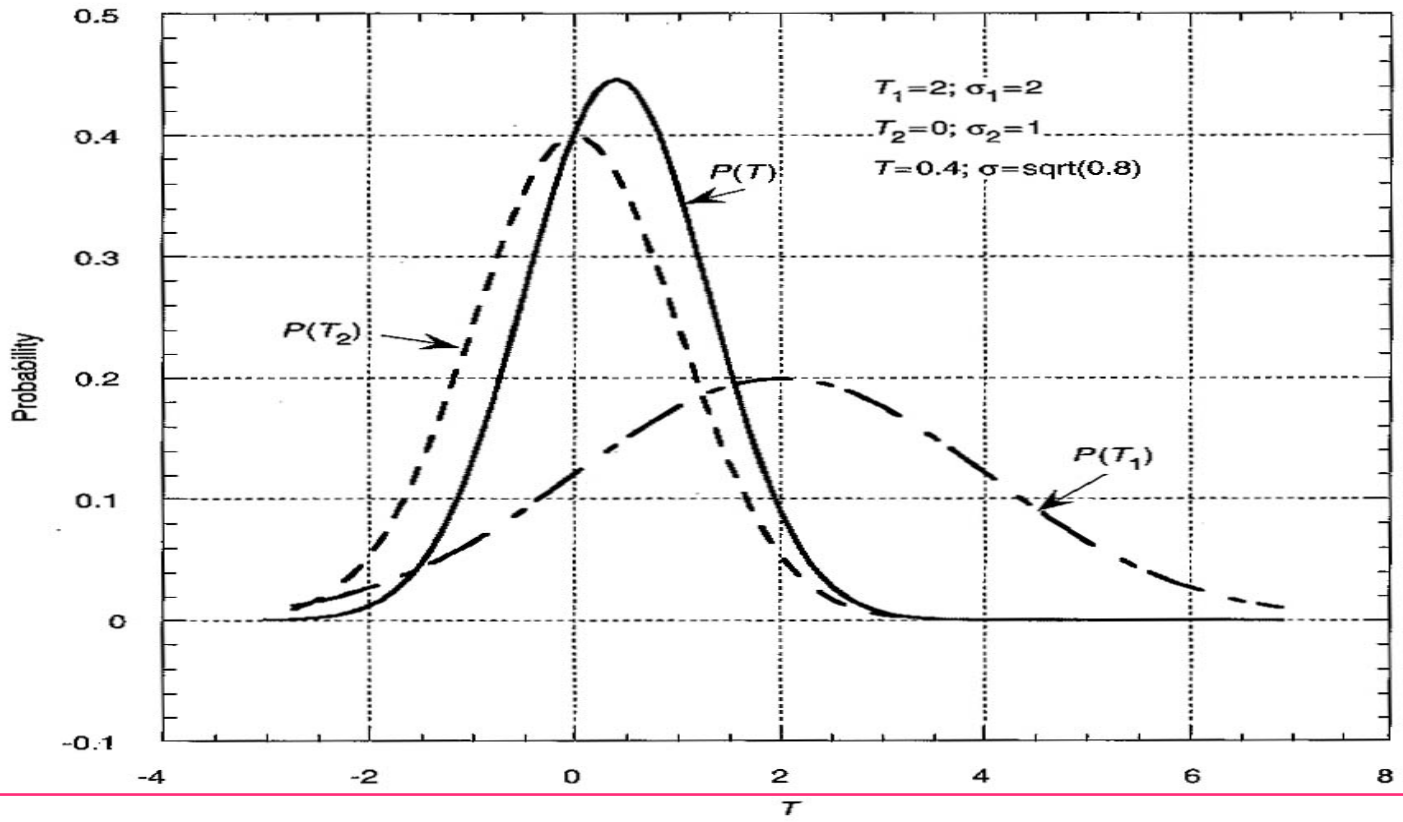
A Simple Example

If T_1 is the background state with std of σ_1 ; T_2 is the observation with std of σ_2 , then the posterior analysis T and its std σ will be:

$$T = T_1 + K\,(T_2 - T_1); \quad K = \sigma_1^{\,2}/(\sigma_1^{\,2}+\sigma_2^{\,2})$$

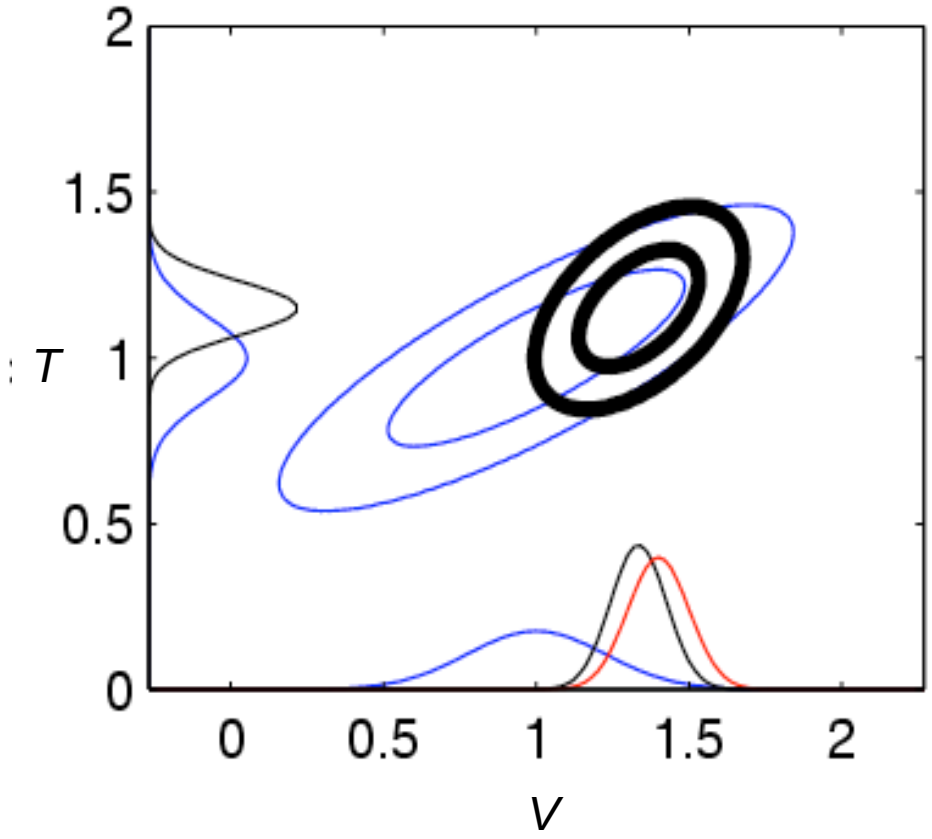
$$\text{or} \quad T = [\sigma_2^{\,2}/(\sigma_1^{\,2}+\sigma_2^{\,2})]\,T_1 + [\sigma_1^{\,2}/(\sigma_1^{\,2}+\sigma_2^{\,2})]T_2$$

$$\sigma^2 = \sigma_1^{\,2}\,\sigma_2^{\,2}\,/(\sigma_1^{\,2}+\sigma_2^{\,2})$$



A Multivariate Example

If T_1 is unobserved but with measurements of V_2 (e.g., radar radial velocity obs), then the posterior analysis T depends on background error covariance Cov(T,V):



$$T = T_1 + K\,(V_2 - V_1)$$

$$K = \mathrm{Cov}(T,V)/(\sigma_{v1}^2 + \sigma_{v2}^2)$$

In EnKF, Cov(T,V) is estimated by short-range ensemble and is flow-dependent

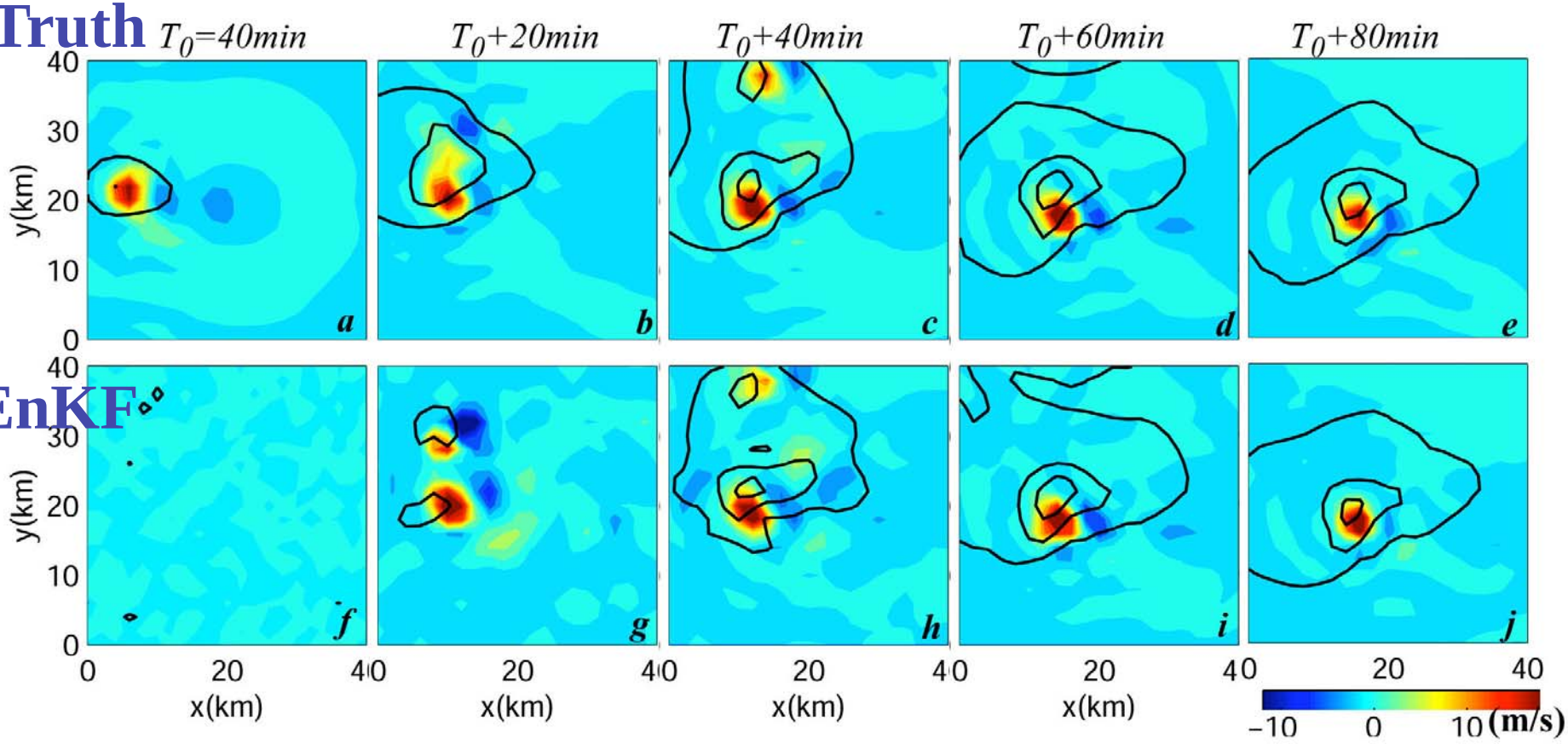
Assimilation of Doppler Radar Observations

Observations: radial velocity V_r only, available every 5 minutes where reflectivity Z>12dBZ

Vertical velocity at 5km (colored) and surface cold pool (black lines, every 2K)

Truth

EnKF

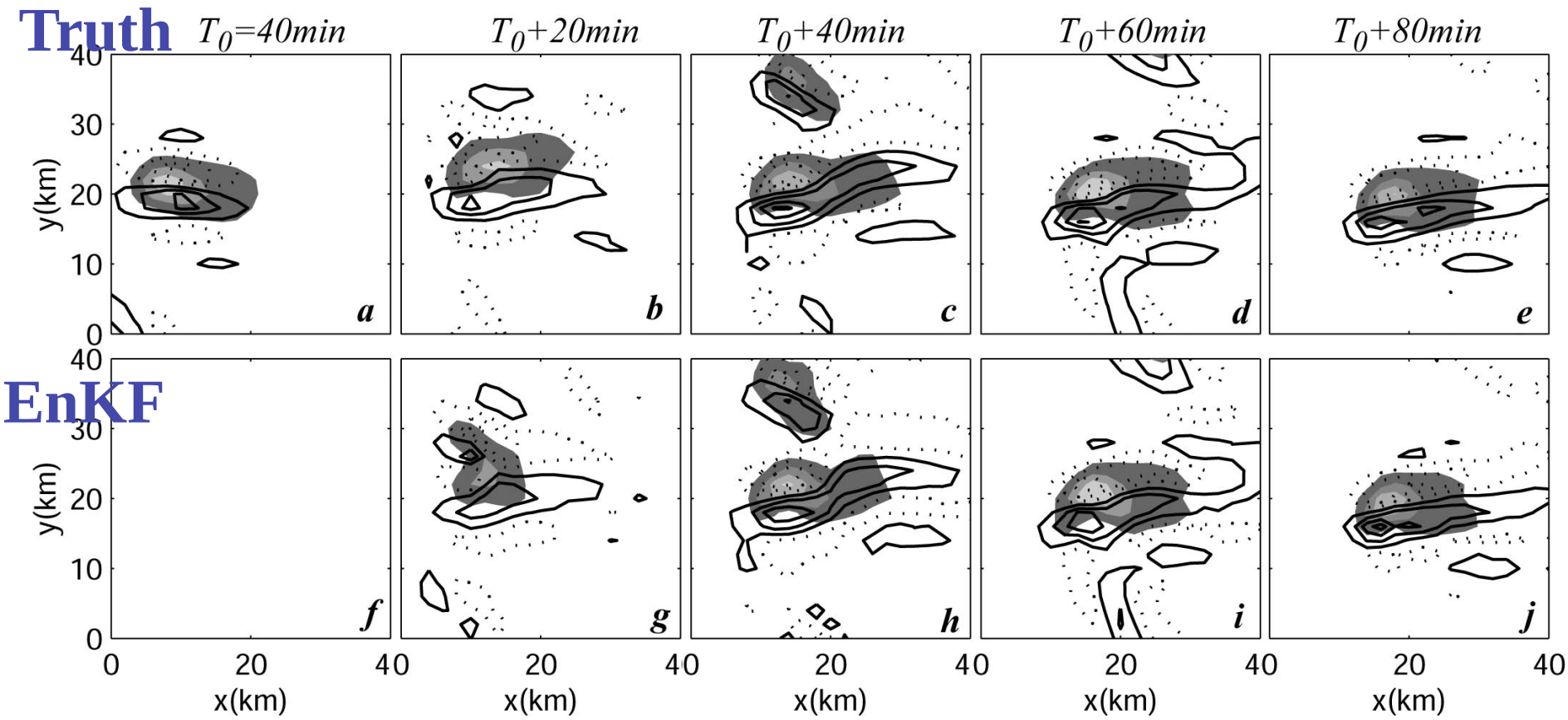


(Snyder and Zhang 2003 MWR; Zhang et al. 2004 MWR; Dowell, Zhang et al. 2004 MWR)

Assimilation of Doppler Radar Observations

Observations: radial velocity V_r only, available every 5 minutes where reflectivity Z>12dBZ

5-km rain water mixing ratio (shaded) and relative vorticity (solid, >0; dotted, <0)



(Snyder and Zhang 2003 MWR; Zhang et al. 2004 MWR; Dowell, Zhang et al. 2004 MWR)

Regional Scale EnKF vs. 3Dvar for June 2003

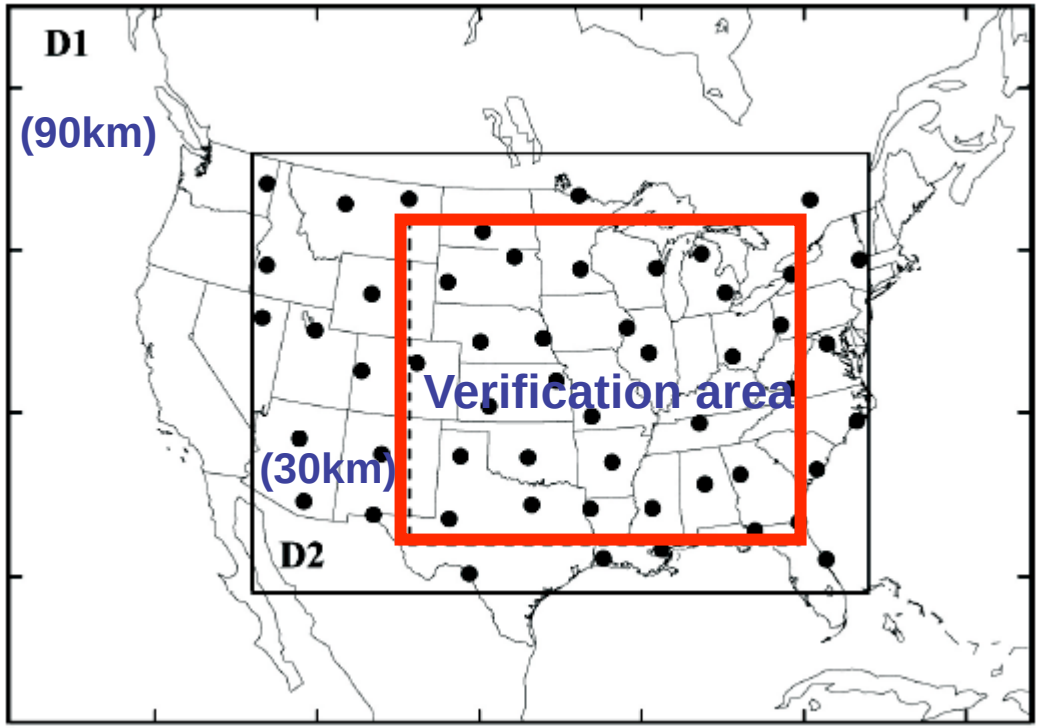
WRF/ARW/EnKF: 40 multi-physics-scheme ensemble

Boundary conditions: D1 updated by 12 hourly GFS/FNL analyses

3DVar: Updated background error covariance with May 2003 forecasts via NMC method (Parrish and Derber 1992; Xiao and Sun 2007)

Observations: Soundings every 12 h QC'd by 3Dvar in D2, assuming observational errors of NCEP.

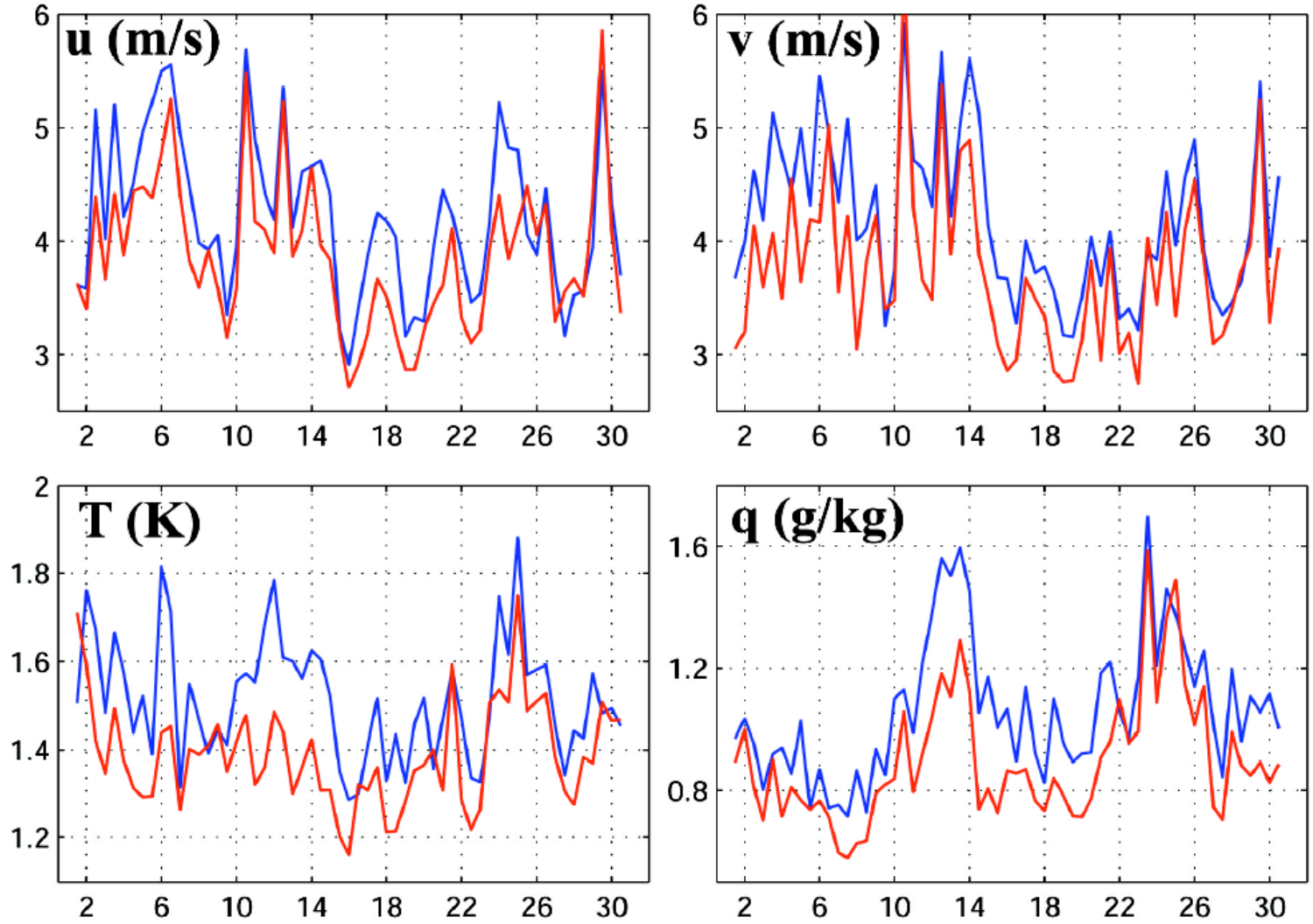
Verification: against soundings at 12-h forecast time and at standard pressure levels



(Zhang, Meng and Aksoy 2006; Meng and Zhang 2007, 2008a,b MWR)

EnKF vs. 3DVar: WRF/ARW 12h forecast RMSE for Jun'03

---EnKF **--- 3DVar_WRF**

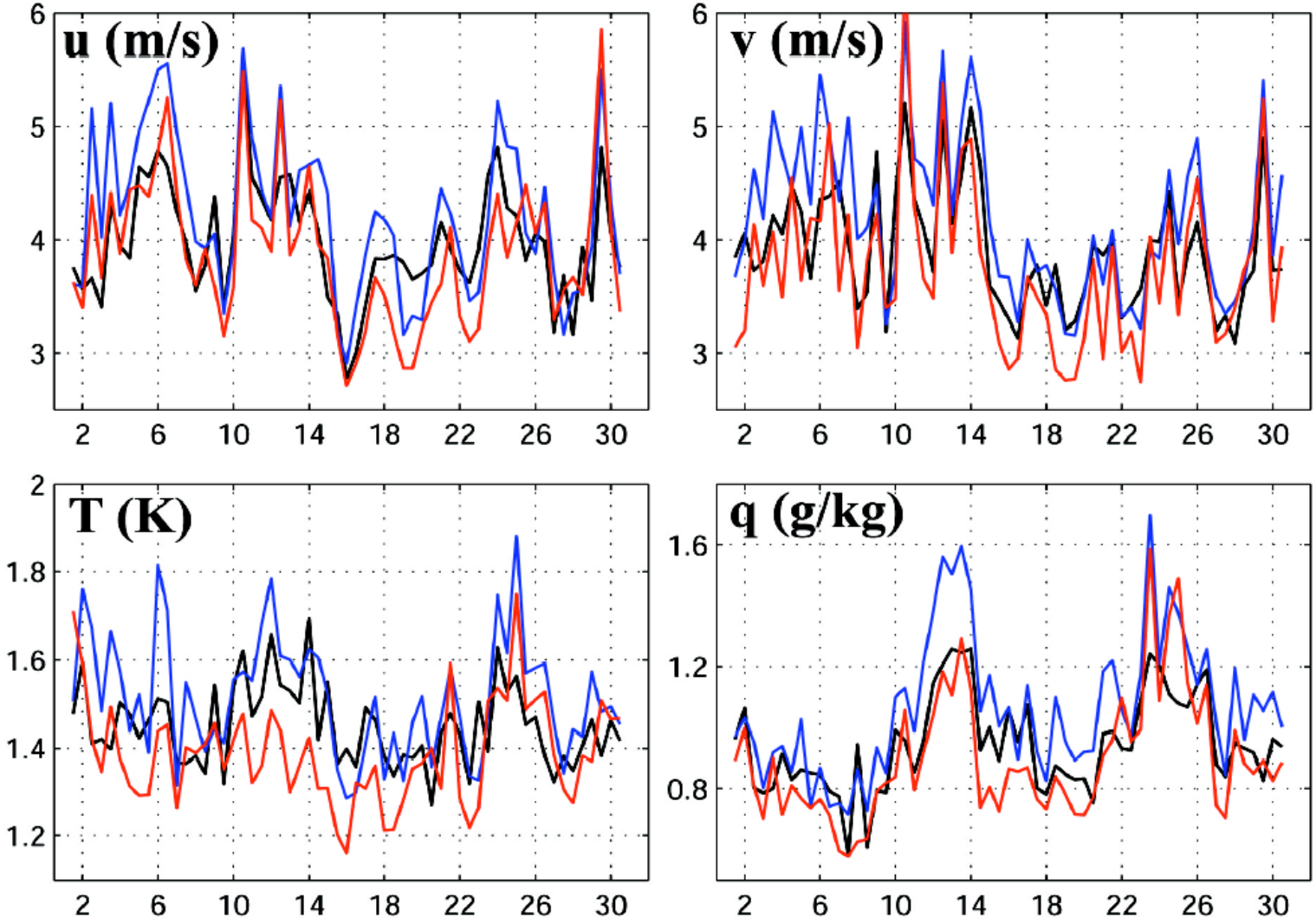


EnKF performs generally better than WRF 3DVar for the whole month of June

(Meng and Zhang 2008b MWR)

EnKF vs. 3DVar vs. FNL_GFS for June 2003

--- EnKF --- 3DVar_WRF --- ARW 12h fcst from FNL_GFS

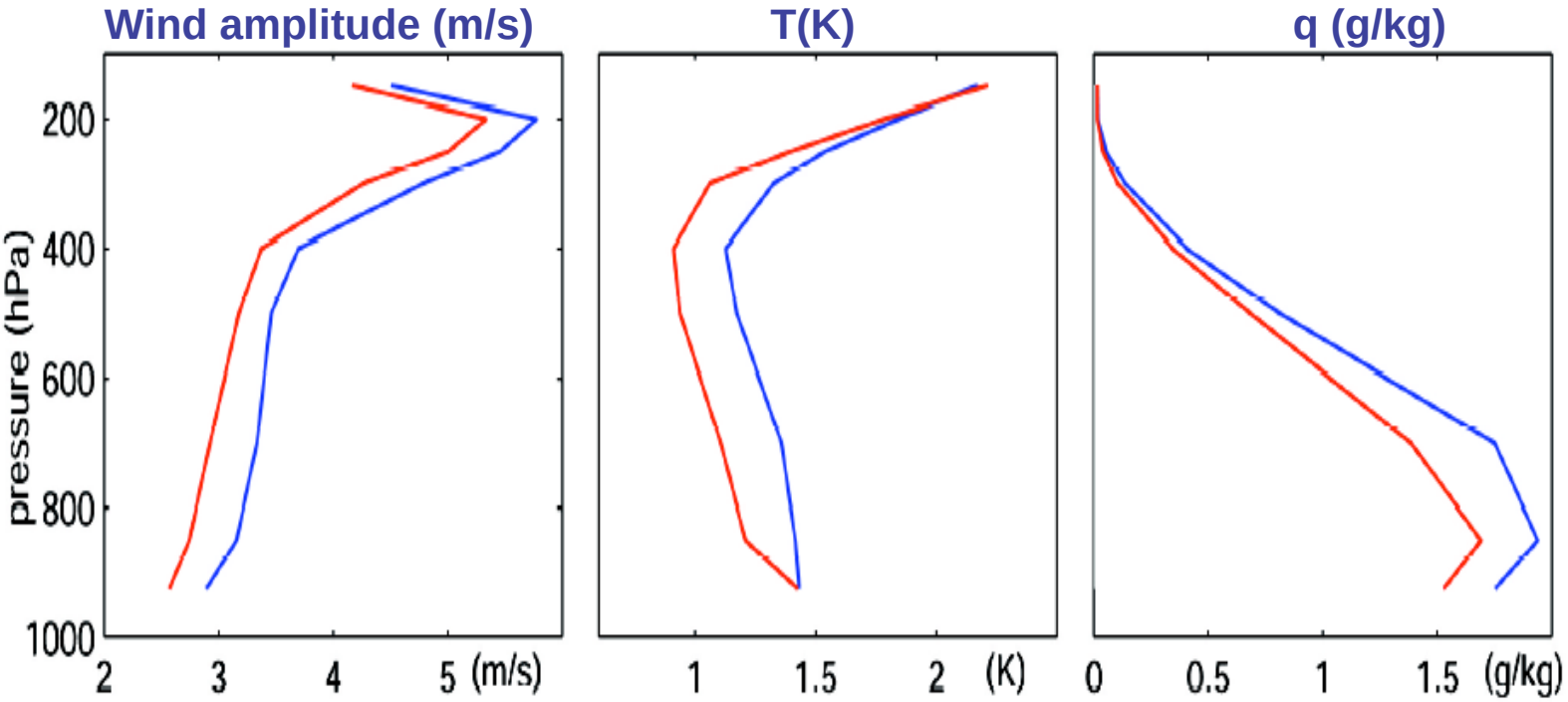


EnKF performs even better than FNL_GFS which assimilates many more data including satellite
FNL_GFS has a generally smaller 12-h forecast error than wrf-3DVar.

(Meng and Zhang 2008b)

Vertical Distribution of 12-h Forecast RMSE for June 2003

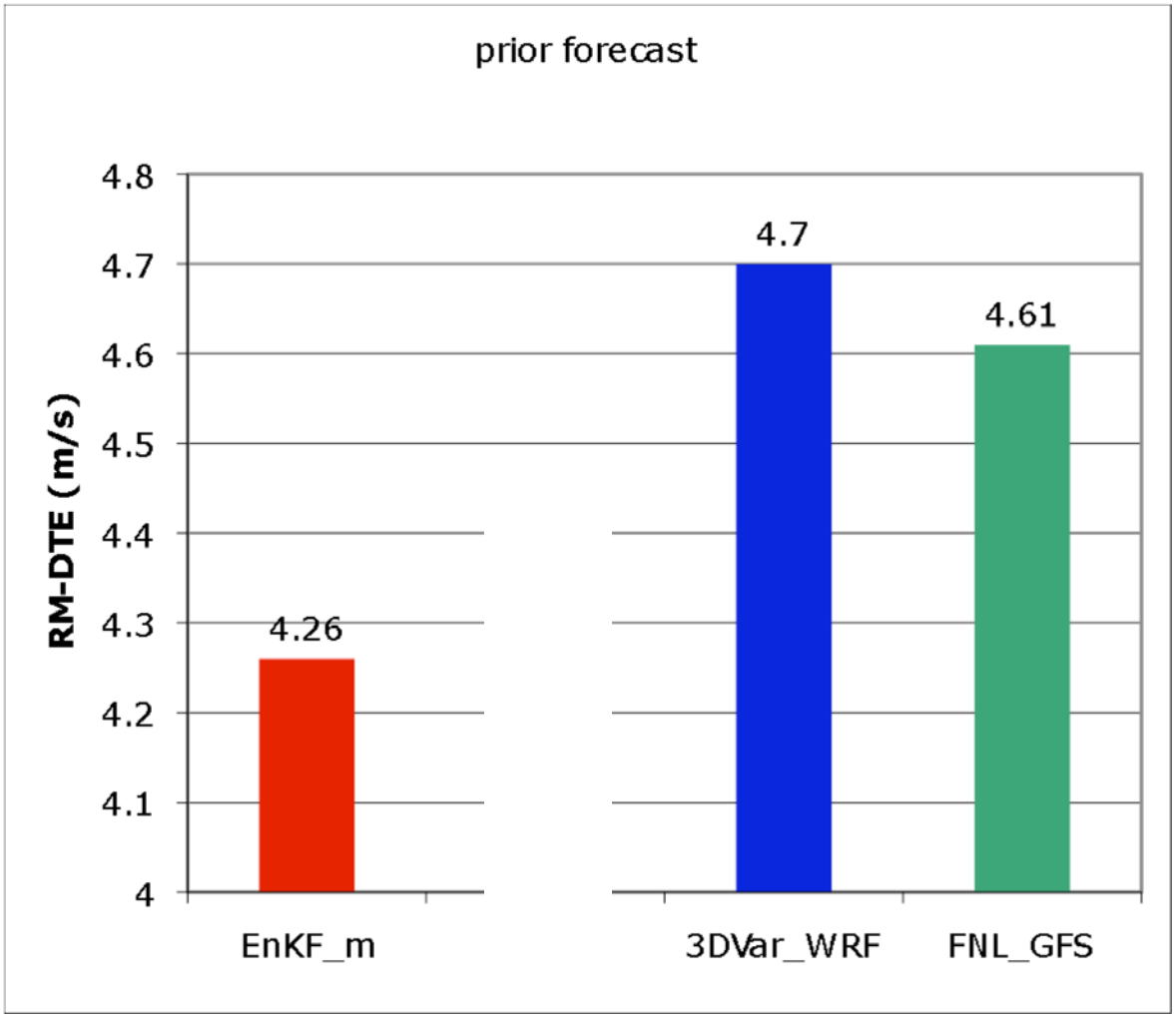
--- EnKF --- 3DVar_WRF



EnKF performs clearly better than WRF-3DVar in almost every vertical level

(Meng and Zhang 2008b)

Monthly Averaged 12-h-Forecast RM-DTE for June 2003

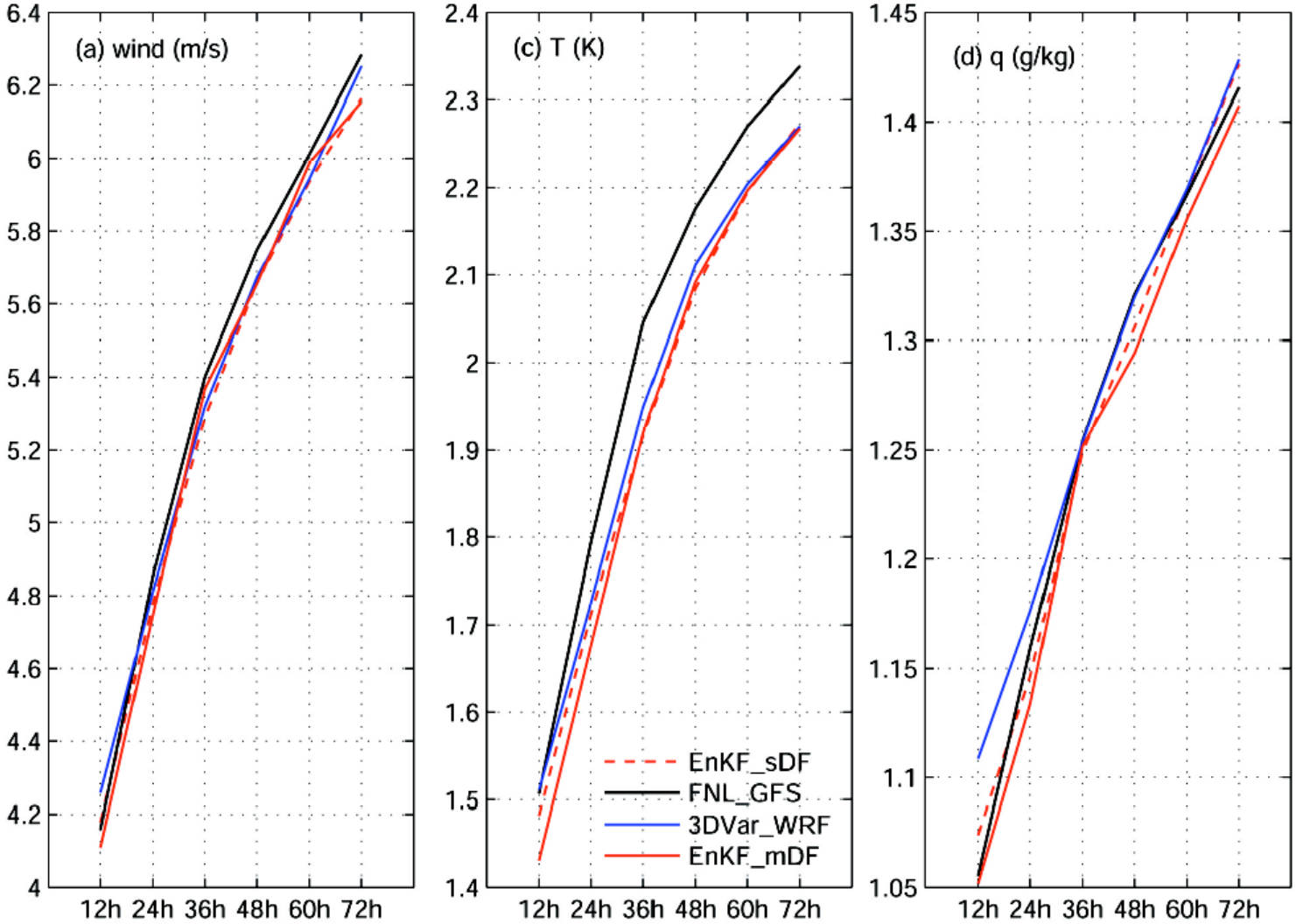


- *EnKF has significantly smaller overall 12-h forecast error than both WRF-3DVar and FNL_GFS.*
- *FNL_GFS has smaller overall forecast error than WRF-3DVar.*

(Meng and Zhang 2008b)

Monthly Averaged Forecast Error at Different Lead times initialized from respective analyses (every 12h, 60 samples)

—FNL_GFS —EnKF —3DVar_WRF

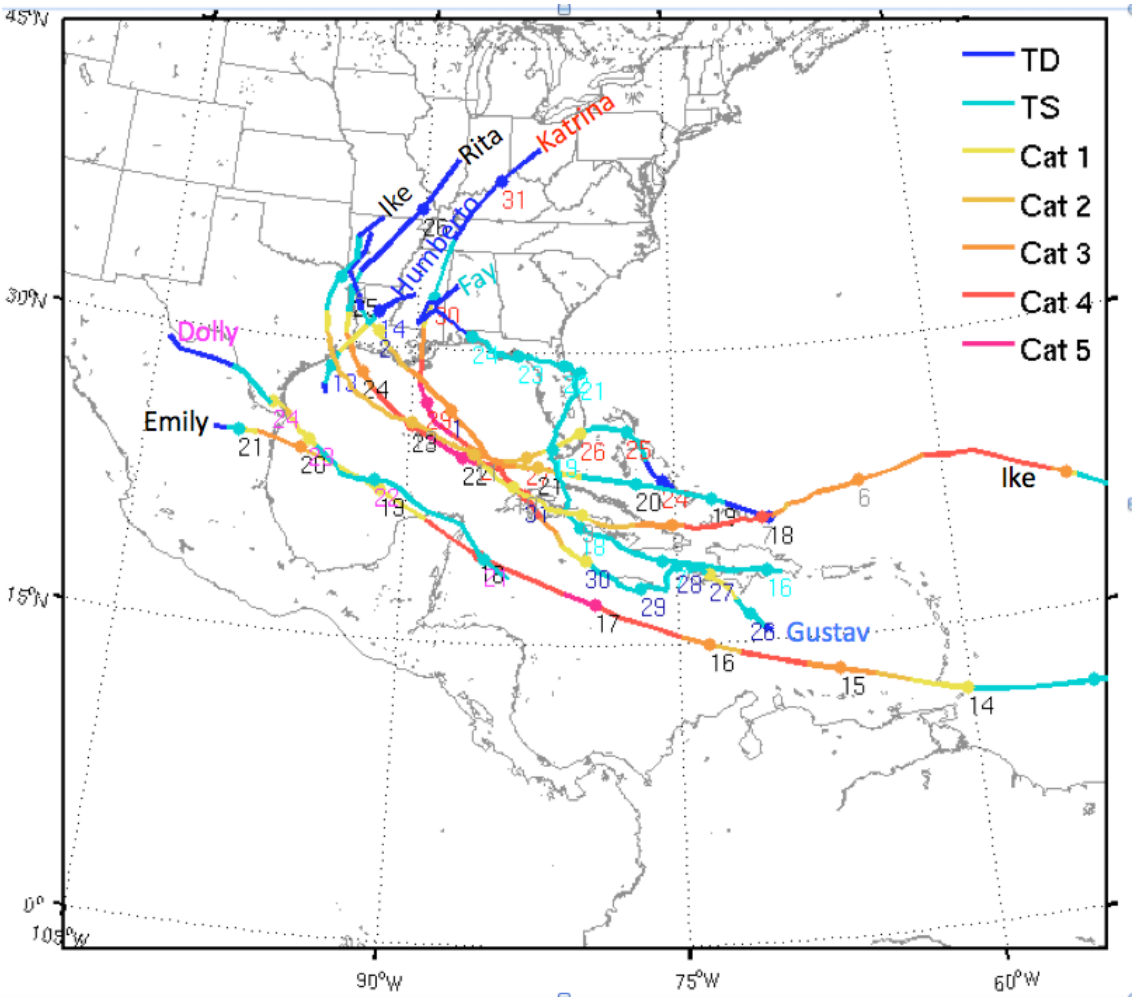


(Meng and Zhang 2008b)

Assimilation of Doppler Vr OBS for Hurricanes

Emily, Katrina, Rita'05, Humberto'07, Dolly, Fay, Gustav, Ike'08

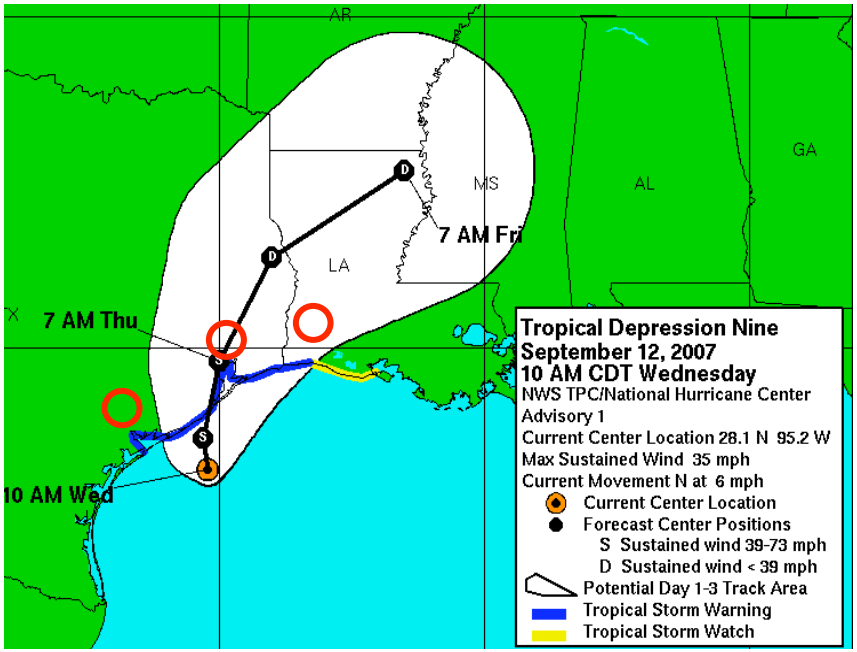
- TC initialization is intrinsically multiscale; initial vortex and convective details can both be important for intensity, structure and precipitation forecasts
- Abundant WSR-88D obs for TCs near coasts
- HRD collects NOAA P3 aircraft radar data sets and process them on most tropical cyclones since 1994.
- NOAA airborne Doppler missions to expand for TCs



Cases with WSR88D or NOAA P3 airborne Vr OBS

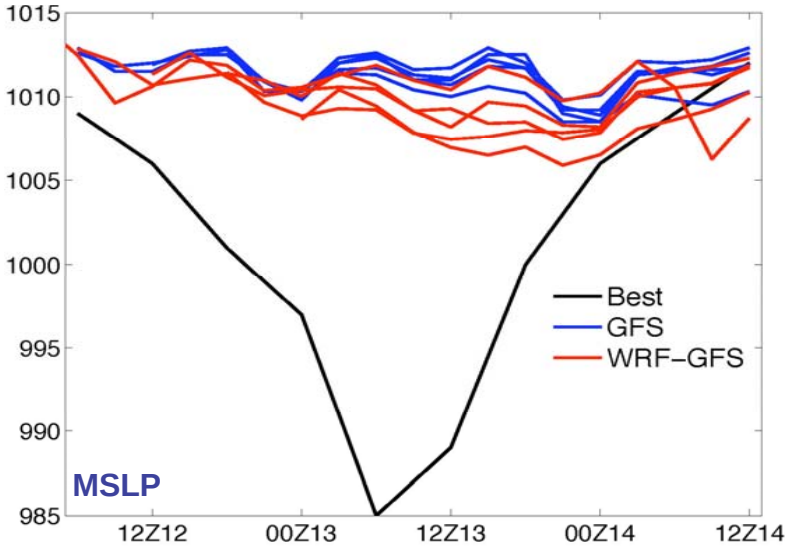
Coastal Storms within WSR-88D: Hurricane Humberto (2007)

***Synopsis*:** first lanfalling hurricane at US coast since busy 2005 season; fastest from first NHC warning to a category 1 hurricane; 70 million estimated property damage, 1 death



It becomes a hurricane 14hr after this NHC forecast.

*GFS (**blue**) & 4.5-km WRF (**red**) forecast: No forecast initialized with GFS FNL analysis ev 6hr from 00Z 12 to 00Z 13 predicts rapid formation*



(Zhang et al. 2008, MWR, in review)

Assimilate W88D Vr for Humberto with EnKF

- **WRF domains:** **D1-D2-D3-D4 grid sizes---40.5, 13.5, 4.5, 1.5km (movable)**
  - **Physics: WSM 6-class microphysics; YSU PBL; Grell-Devenyi CPS**

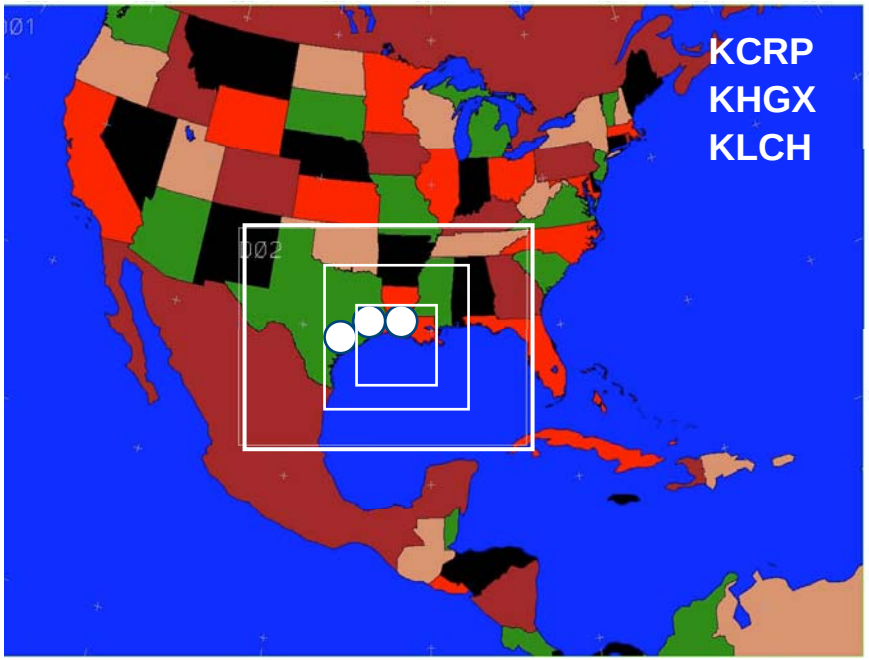
- **EnKF (Evensen 1994; Meng & Zhang 2008a,b): - 30-member ensemble**

  - Initialized at 00Z 12 using 3DVar background uncertainty with FNL analysis; GFS forecast used for boundary condition in forecasts

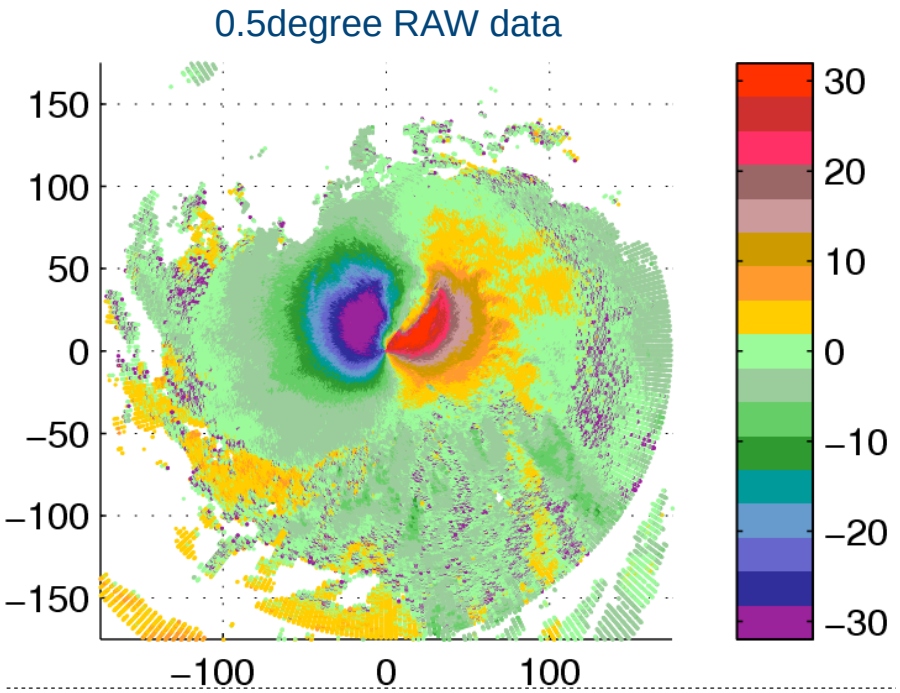
  - Advantage: flow-dependent background error covariance from ensemble; flow dependent analysis uncertainty for ensemble forecasting

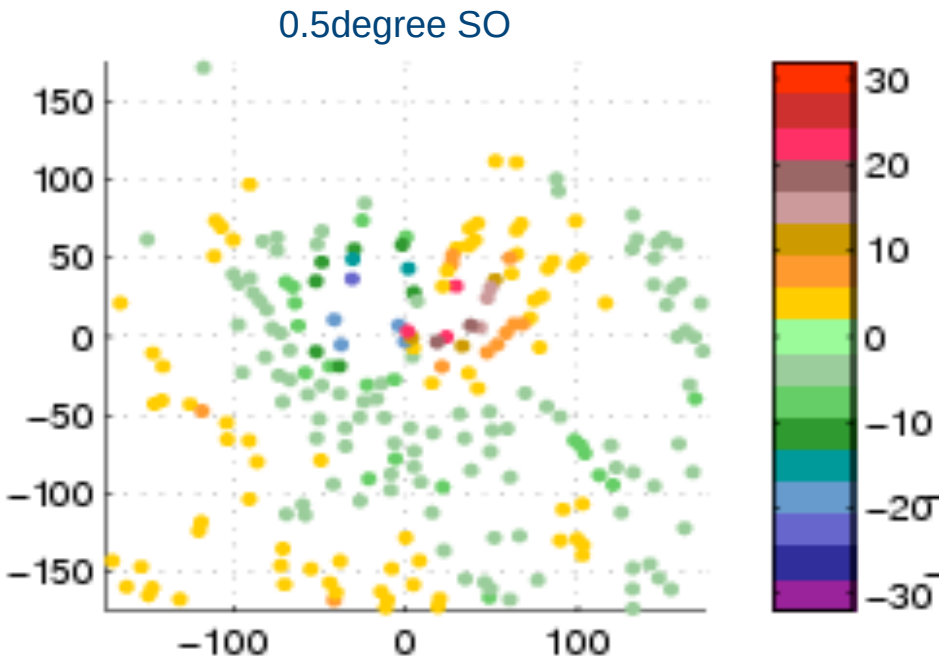
- **Data assimilated:**
  - **WSR88D at KCRP, KHGX and KLCH radar radial velocity every hour from 09Z to 21Z 12 Sept 2007**

  - **Data assimilation are performed for all domains; obs err 3m/s**



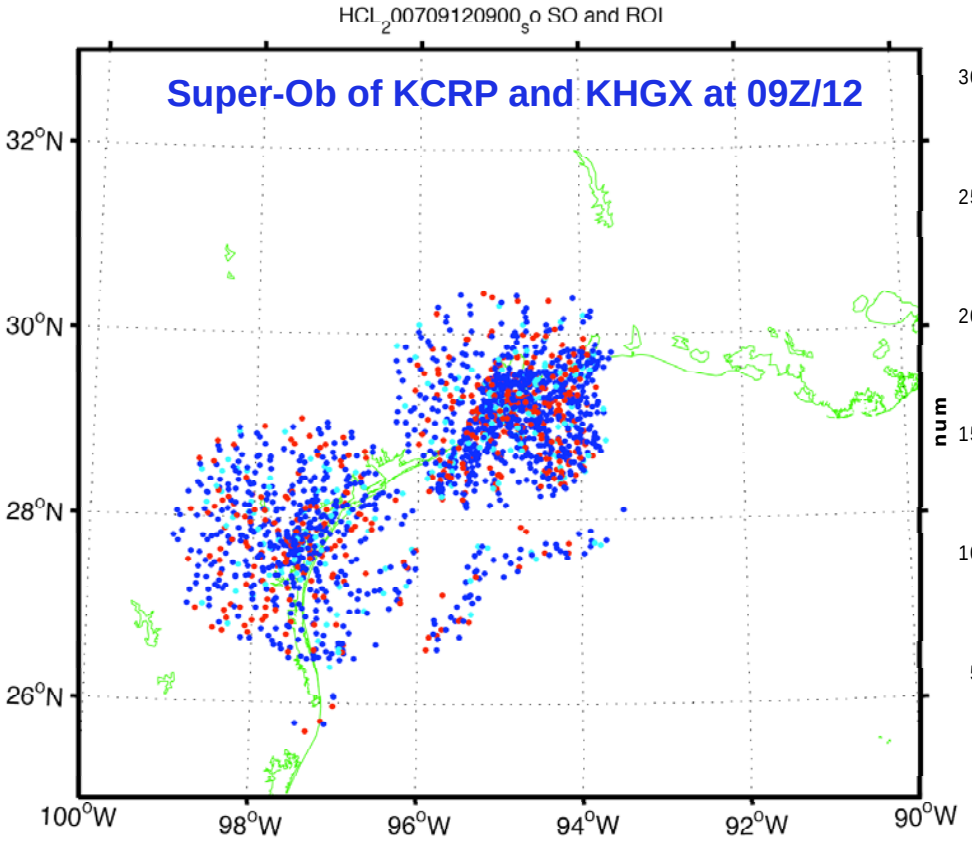
Super-Obs: QC and thinning of WSR-88D Vr Obs

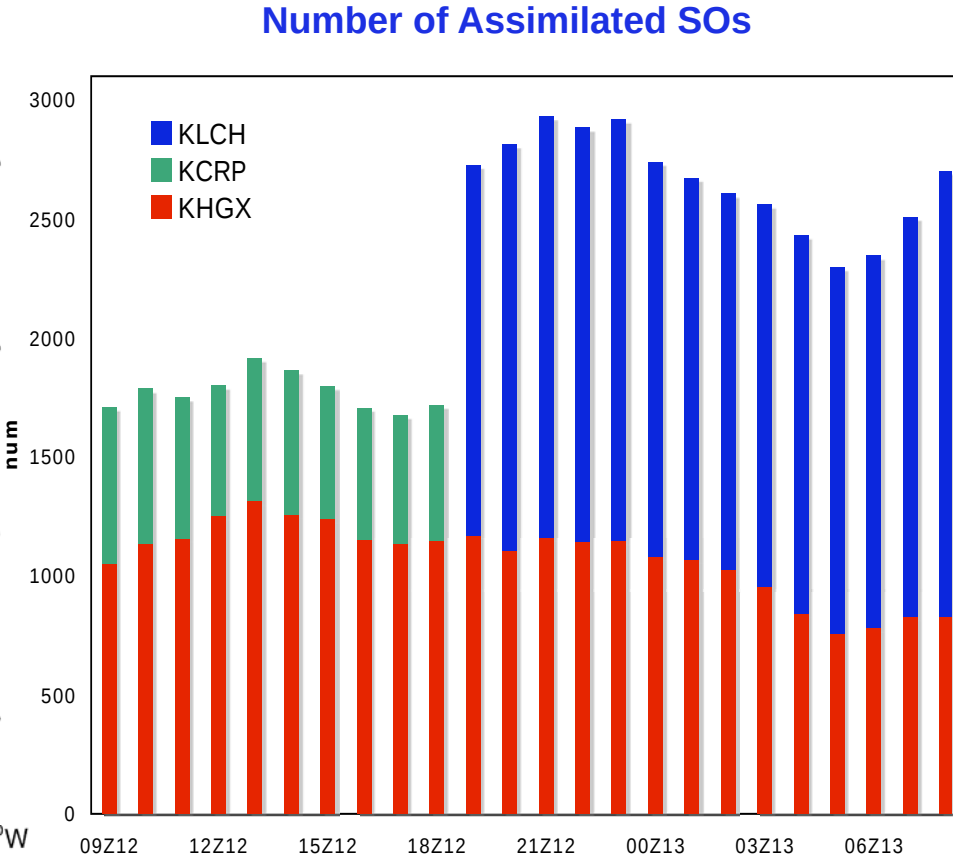




- Define SO position depended on the radial distance
- Average10 nearest data points in the raw polar scan to create a SO
- Averaging bin is 5km max radial range and 5° max azimuthally resolution
- There are at least 4 valid velocity data within an averaging bin.
- The standard deviation checking of the velocities.

Assimilate WSR88D Vr Obs: Number of SOs

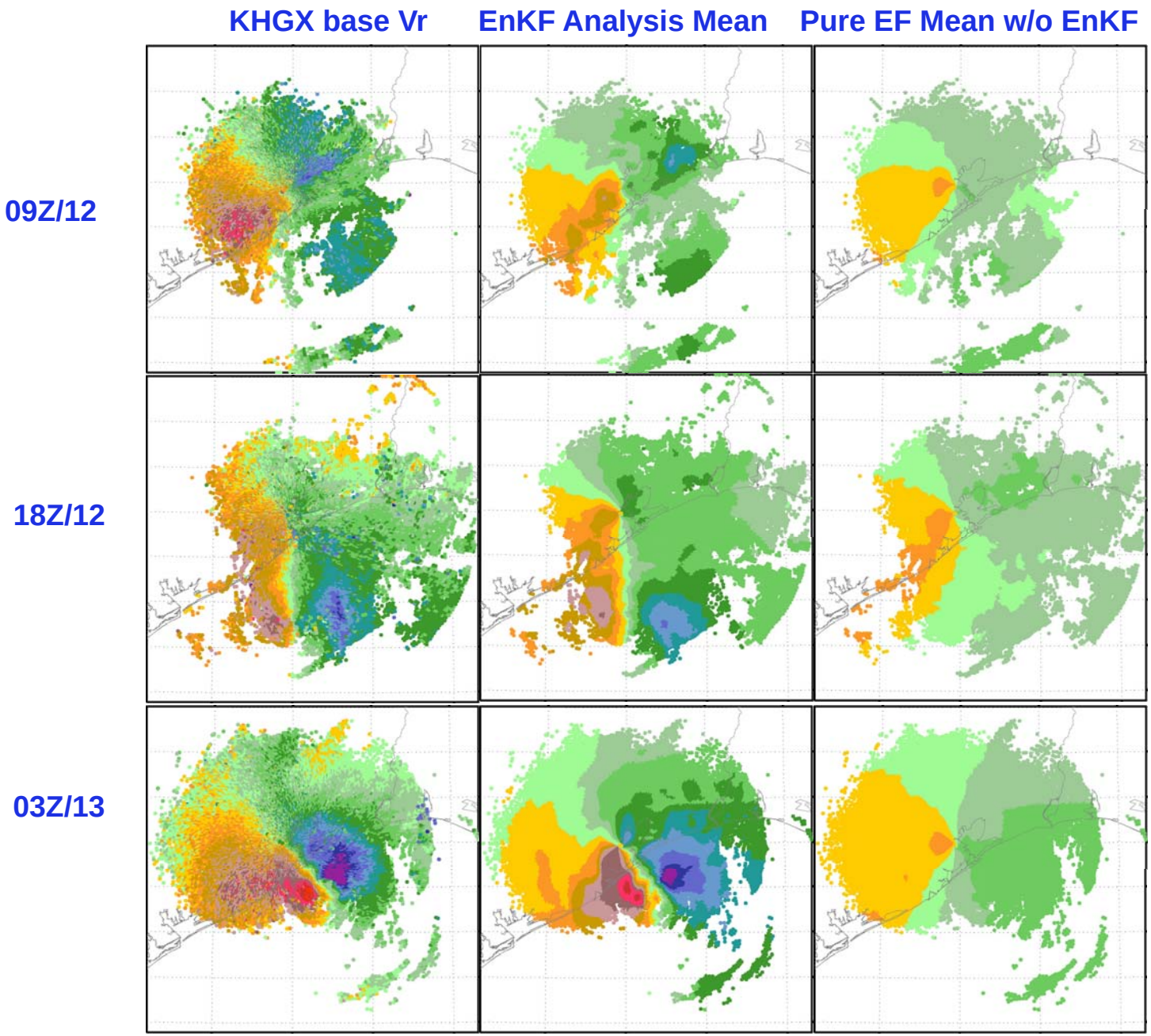




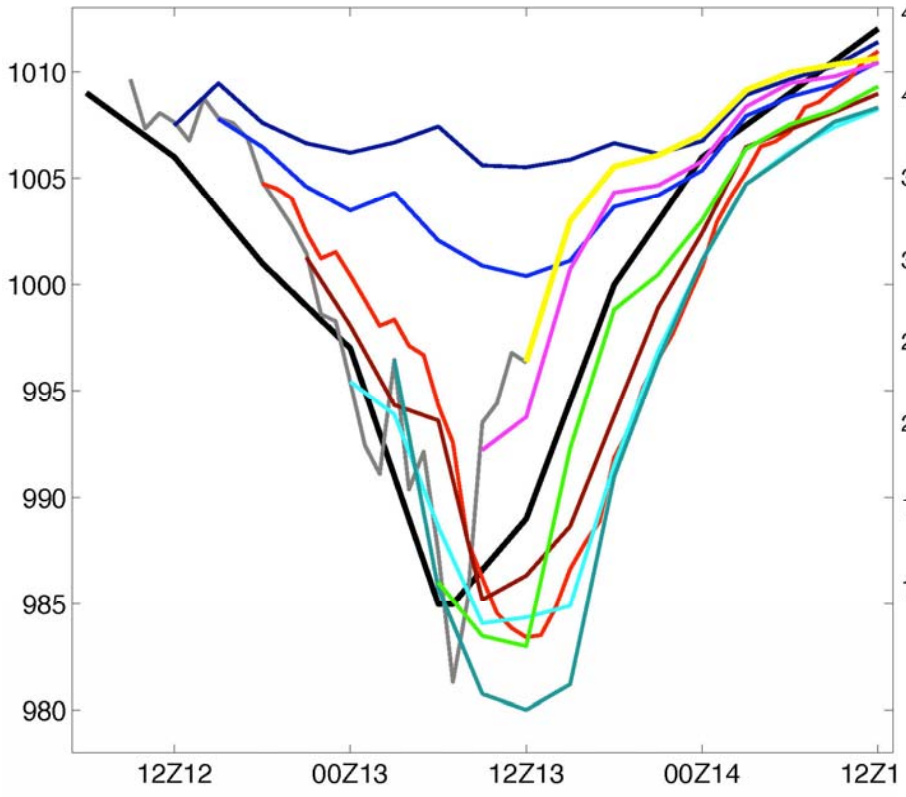
-WRF/EnKF starts assimilating hourly Vr obs of CRP, HGX and LCH WSR88D radars from 09Z/12 to 21Z/12 after a 9-h ensemble forecast from GFS/FNL analysis

-Successive covariance localization with different ROIs for different subset of SOs

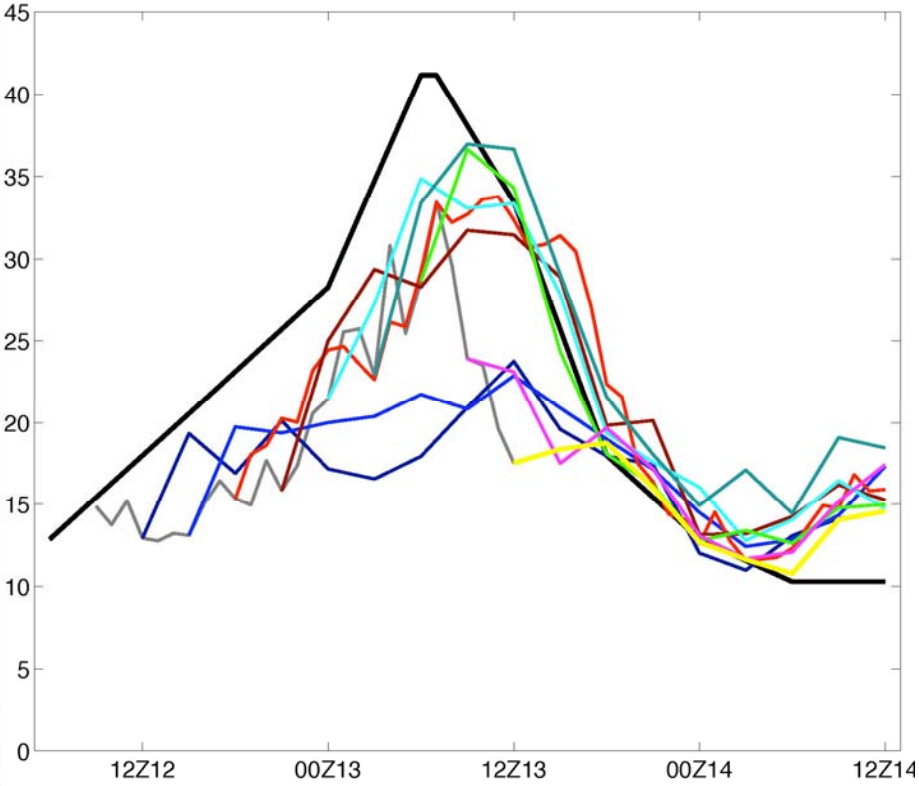
CNTL EnKF Analysis vs. KHGX Obs vs. NoDA



Forecast initialized with EnKF Assimilating WSR88D Vr



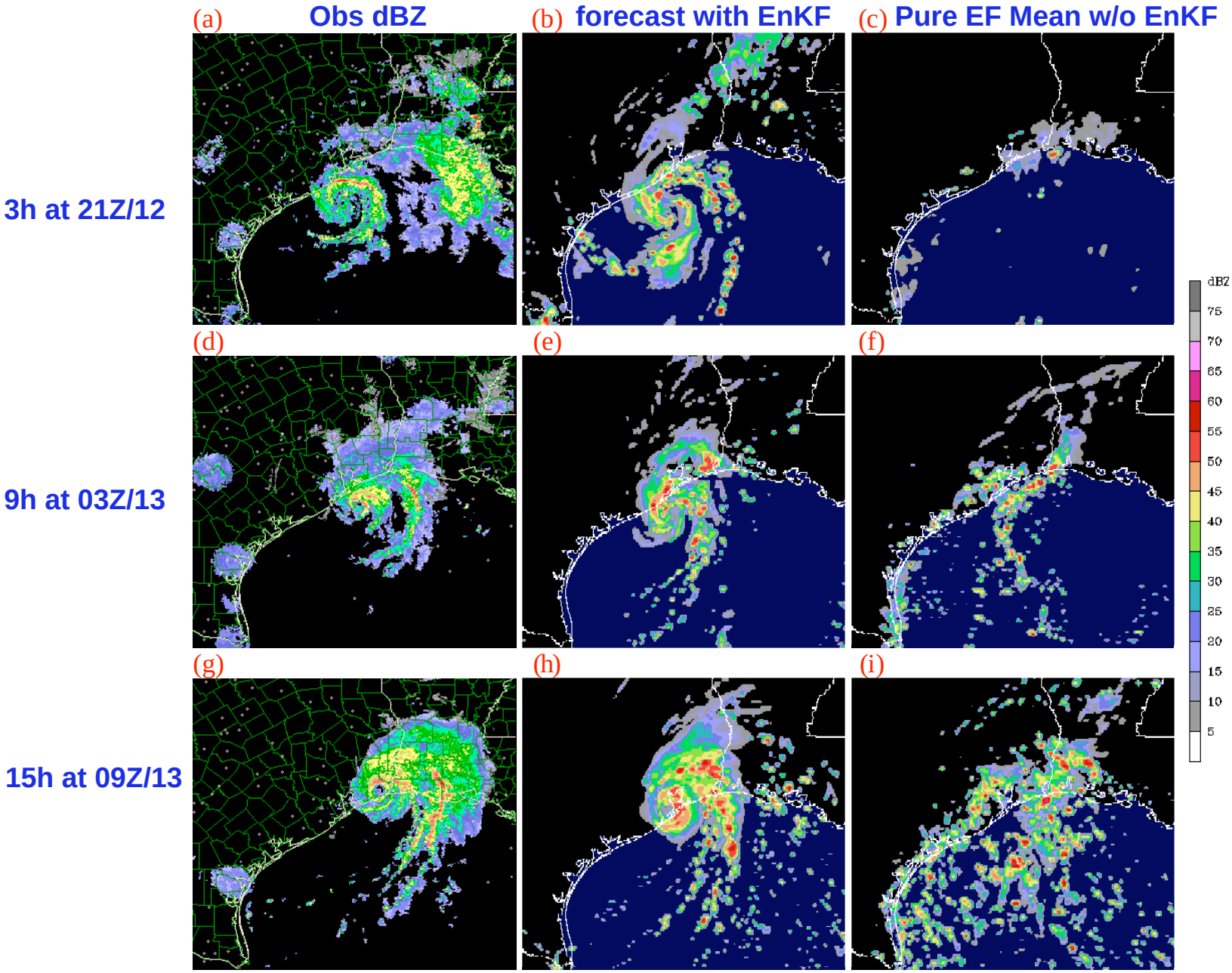
MinSLP (hPa)



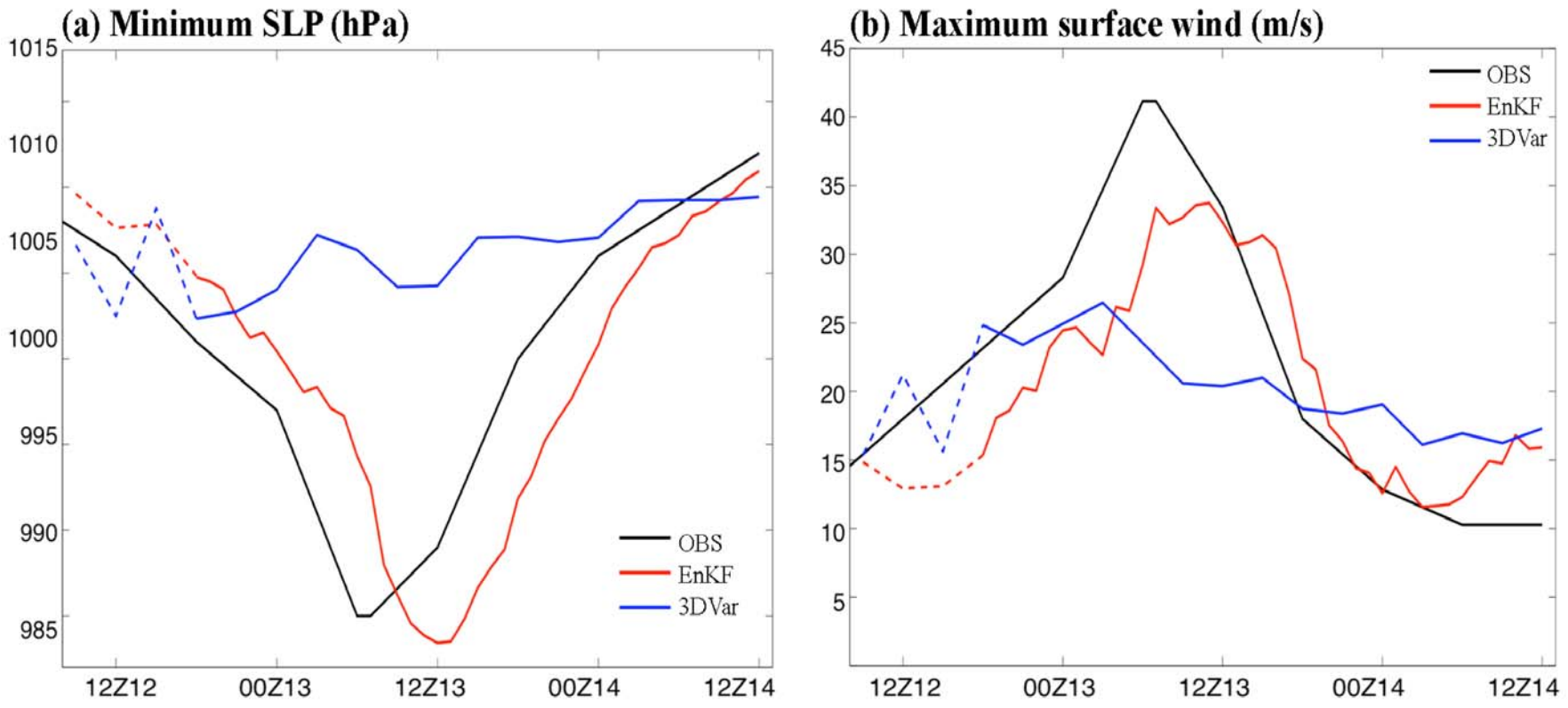
MaxWSP (m/s)

WRF single forecasts initialized with EnKF analysis at 18Z or 21Z September 12 captures well the rapid TC formation and deepening (red and brown)

Forecast from EnKF Analysis at 18Z/12

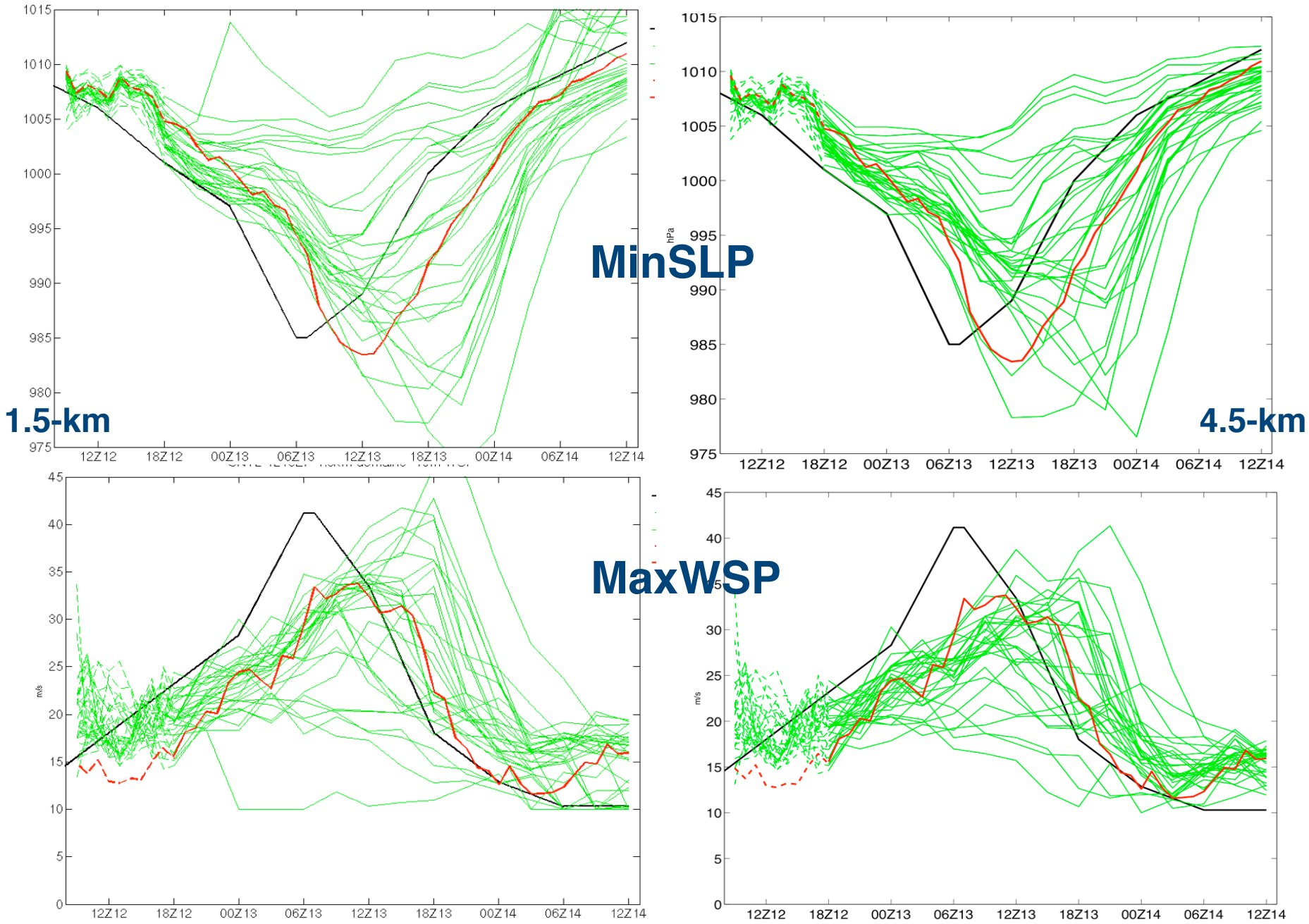


Comparison with WRF/3DVAR Assimilating the Same OBS



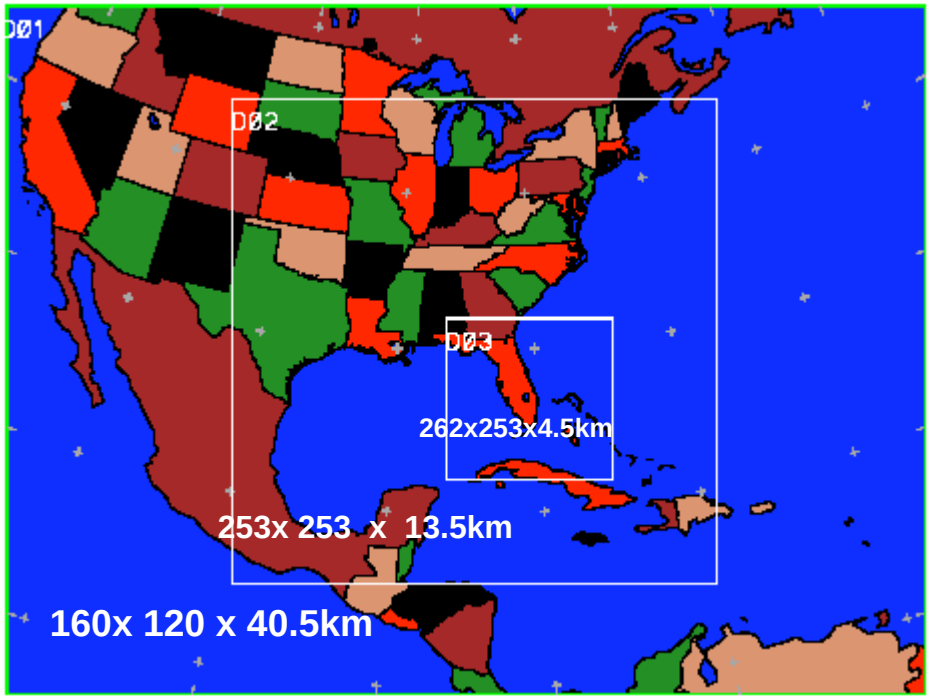
Without flow-dependent background error covariance, WRF/3DVAR forecast failed to develop the storm despite fit to the best-track obs better at 18Z

Predictability: 1.5-km (left) vs. 4.5-km (right) 42h ensembles

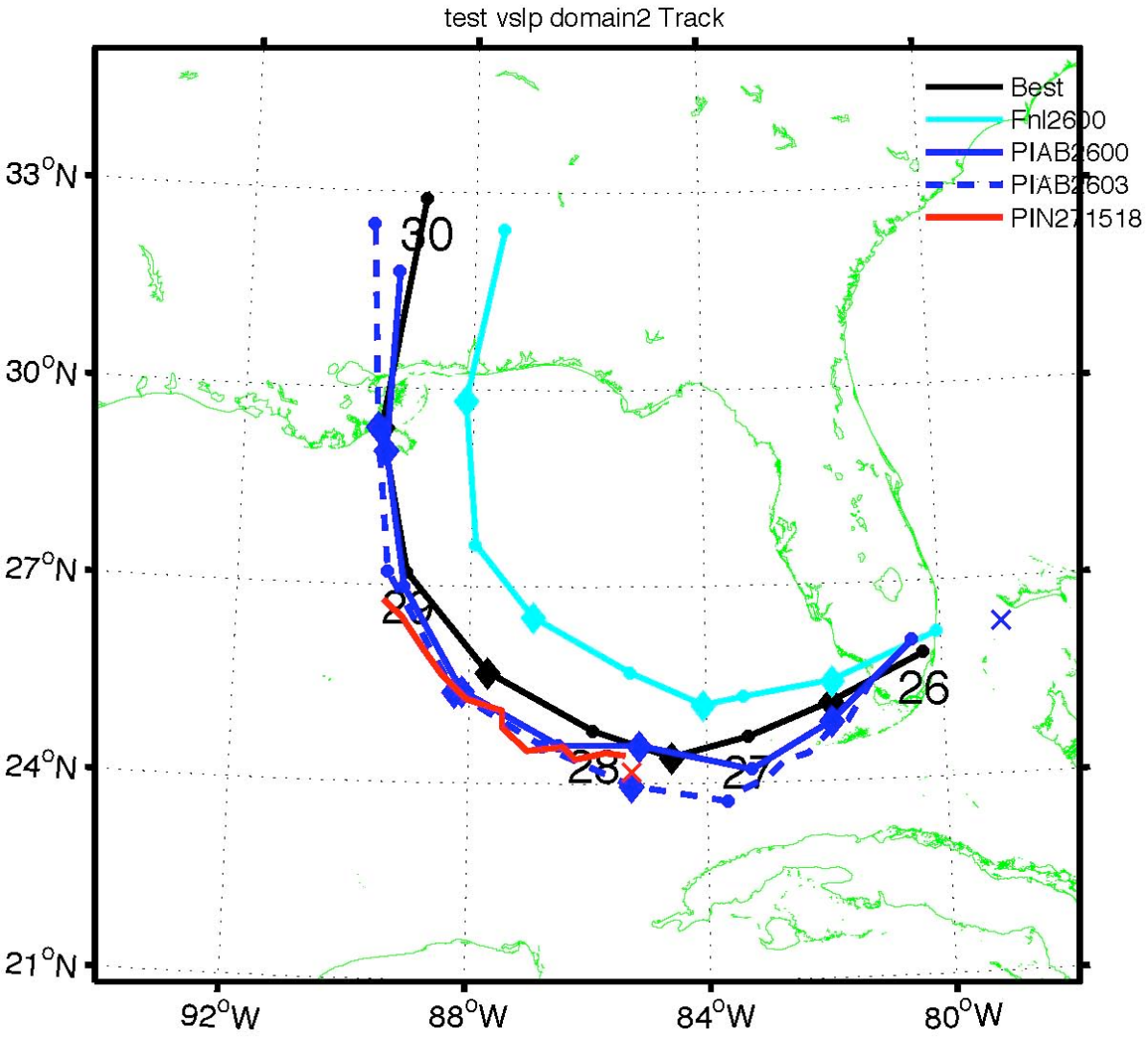


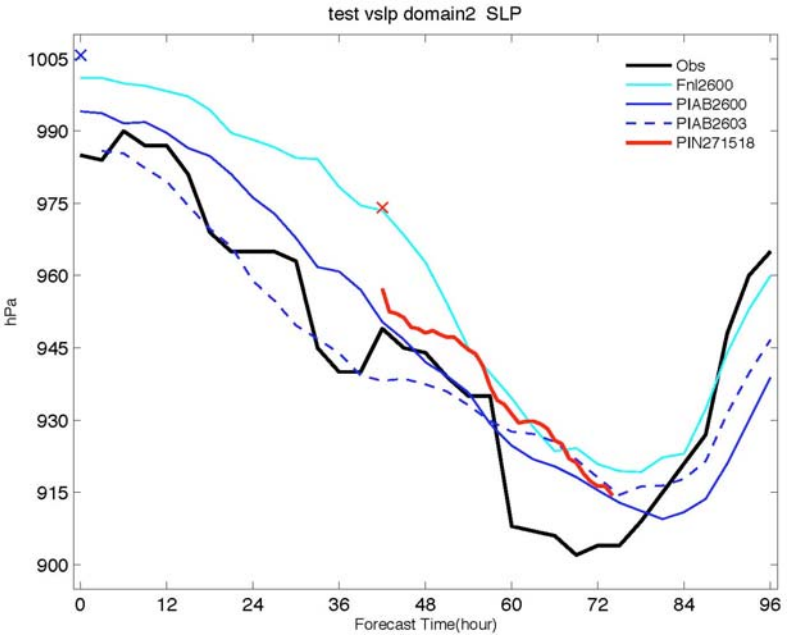
WRF/EnKF for Katrina with W88D Data

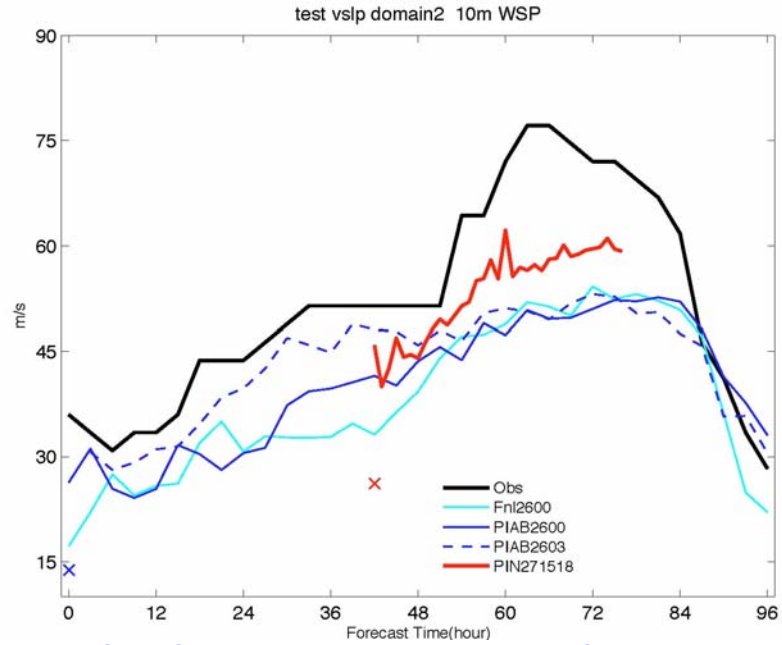
- WRF domains D1-D3: 40.5, 13.5, 4.5 km ; 35 vertical levels; WSM 6-class microphysics; YSU PBL; Grell-Devenyi CPS
- EnKF (Meng & Zhang 2008a,b) but with 30-member single-scheme ensemble; Gaspairi&Cohn 99' covariance localization but with varying RoI
- IC & BC: FNL analysis using 3DVAR background uncertainty
- Data assimilated:
  - TC position (err=20km) and intensity (err=1hpa) D1,D2 every 3 h from 0Z/25 to 0Z/26 (Chen and Snyder 2007)
  - Doppler velocity (err=3m/s) from KMAX and KBYX (D1, D2) at 00Z/26 and/or 03 & 06Z
- Forecast: 96-h single run from mean analysis with D1, D2, D3 (two-way) w/ D3 movable



EnKF Performance: Track forecast with Vr assimilated







NEXRAD at KAMX and KBYZ assimilate at 00Z 26 Aug in 14.5-km D2; free forecast with 4.5-km D3 afterwards

Airborne Doppler Radar Scanning Geometry

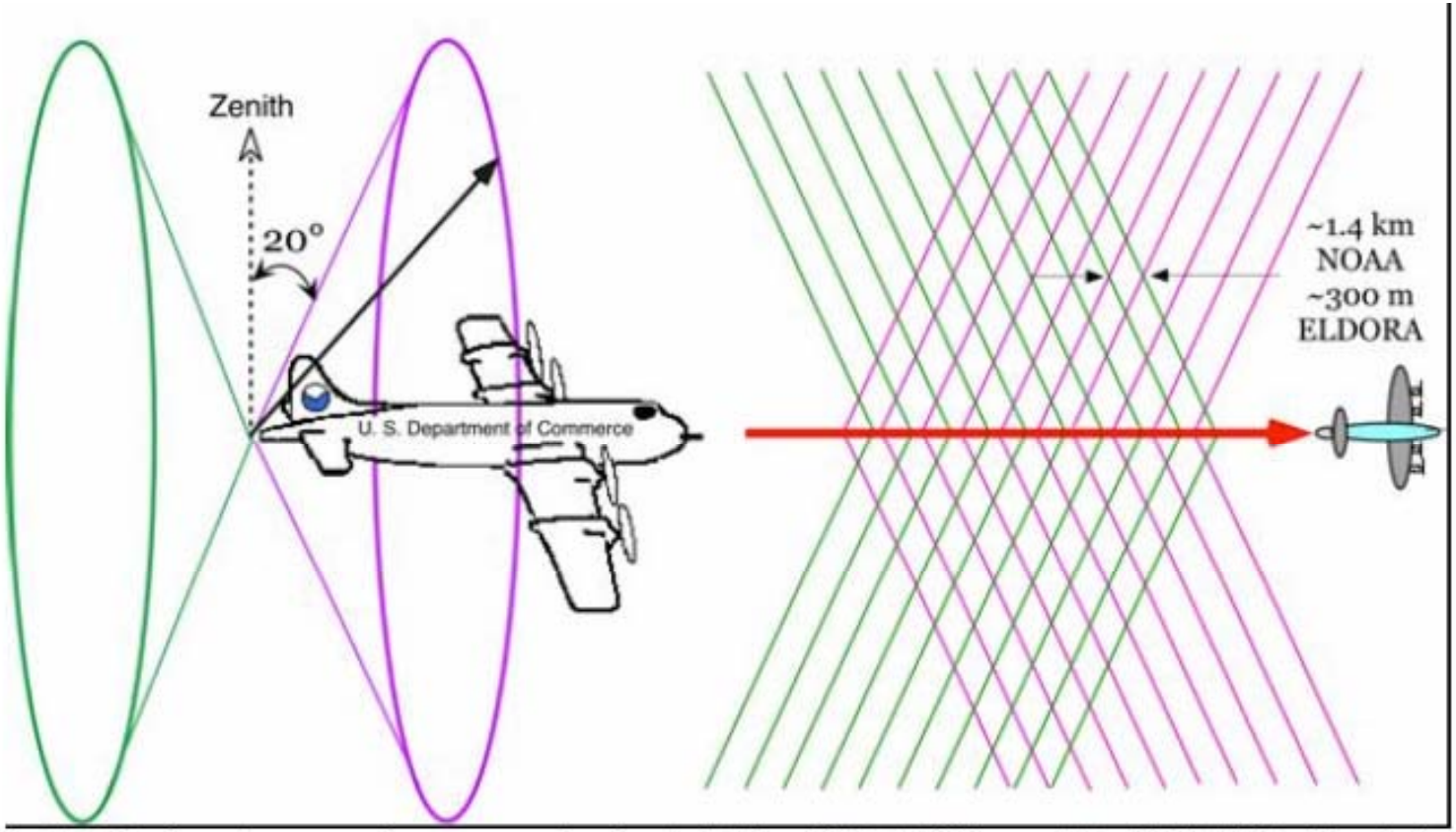
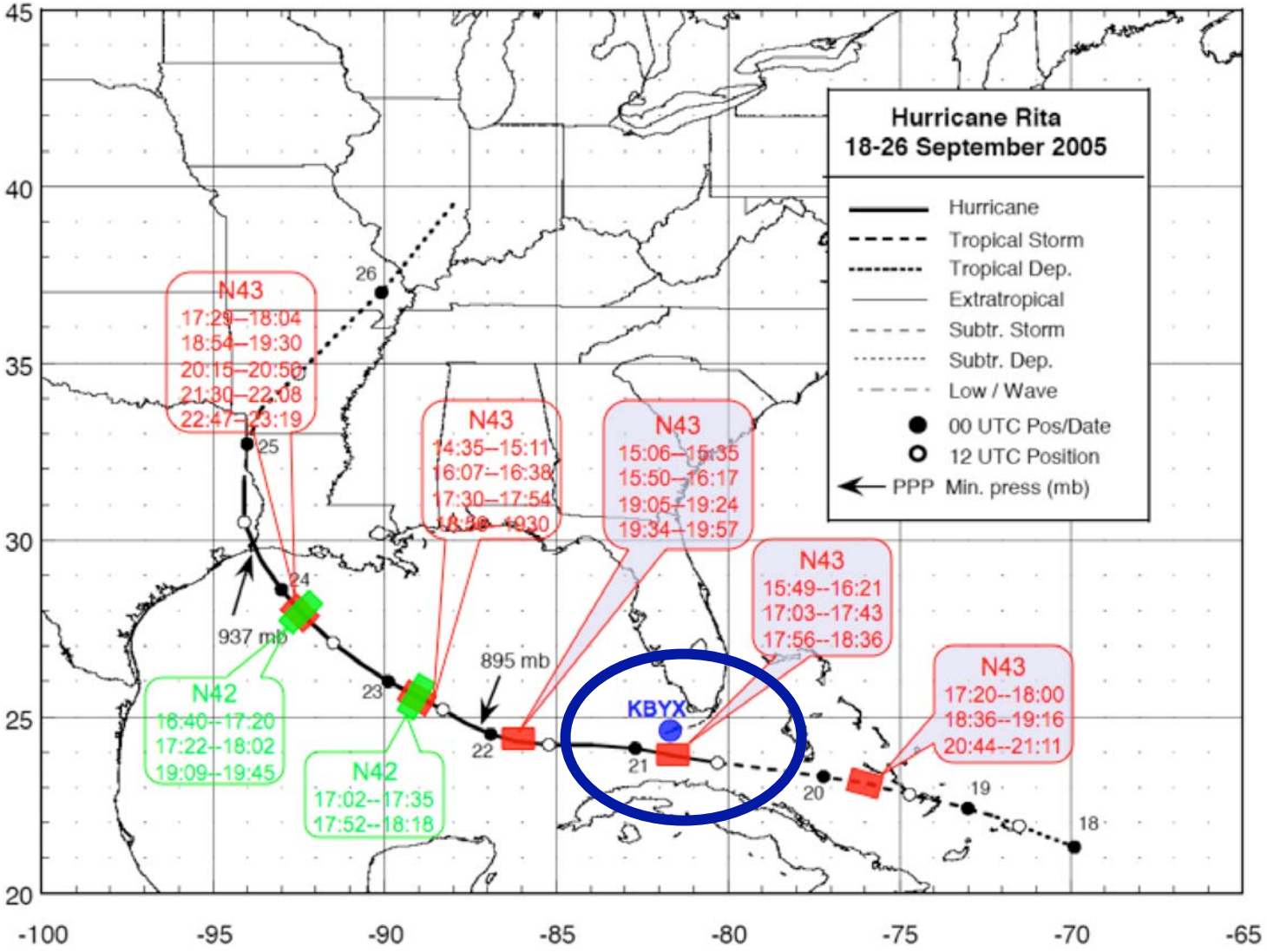


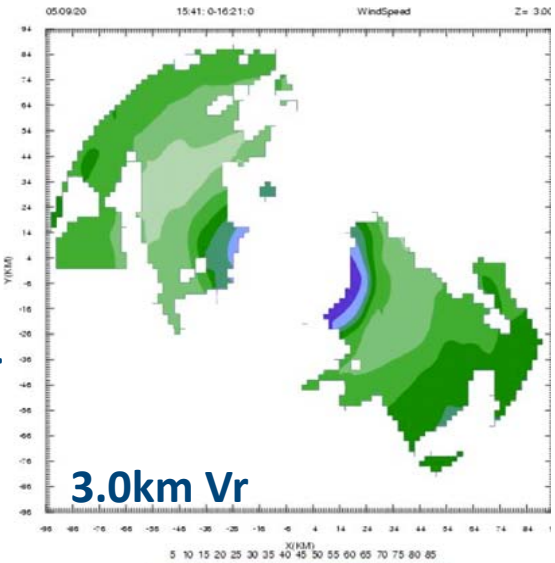
Fig. 2.5 Tail radar scanning geometry for both the NOAA P-3s and the NRL P-3. The left plot shows a schematic of the antenna scanning methodology. A horizontal projection of the beams is shown on the right.

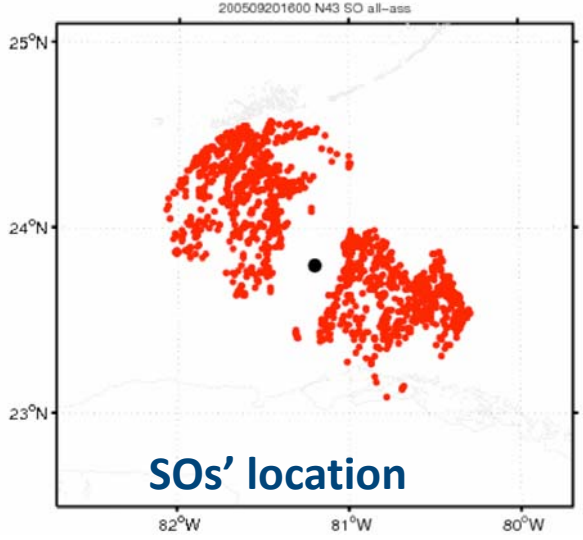
Hurricane Rita (2005): Best track and NOAA P3 Airborne Missions



Airborne Vr Super-Observations (SOs): Similar to W88D but more QCs

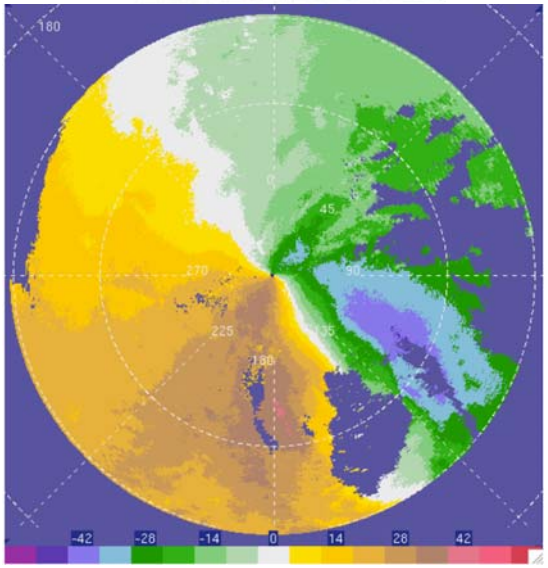
Airborne 20050920 15:41→16:21

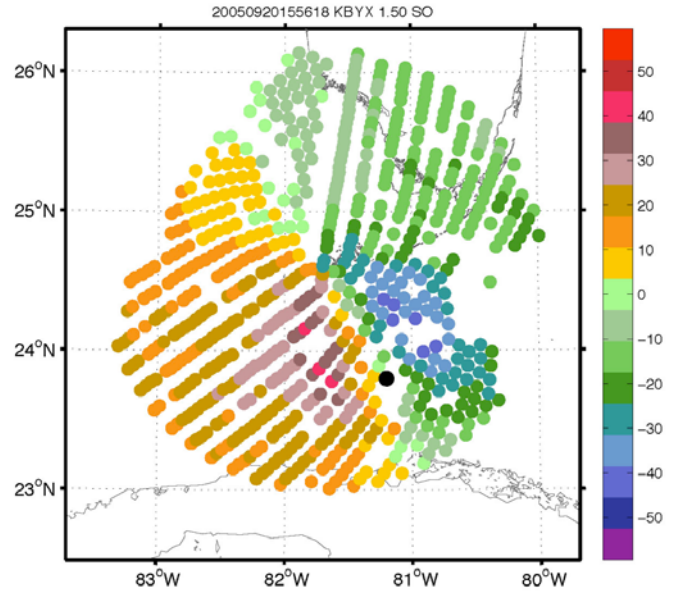




All SOs

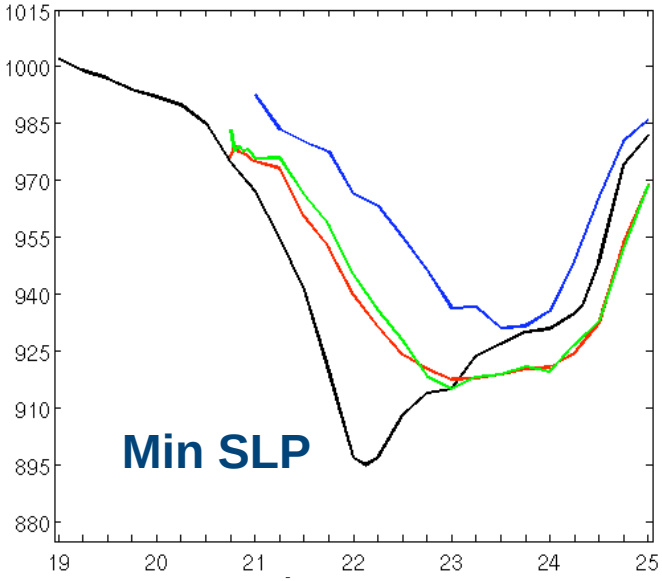
KBYX 20050920 15:55:56' 1.50 degree elevation

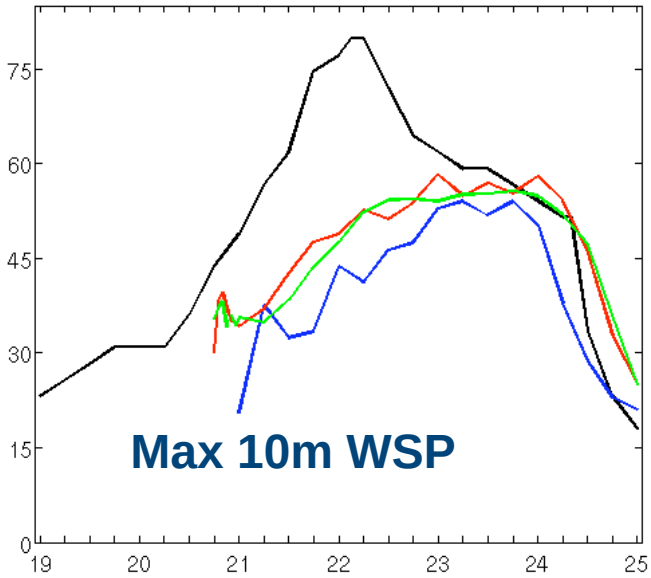


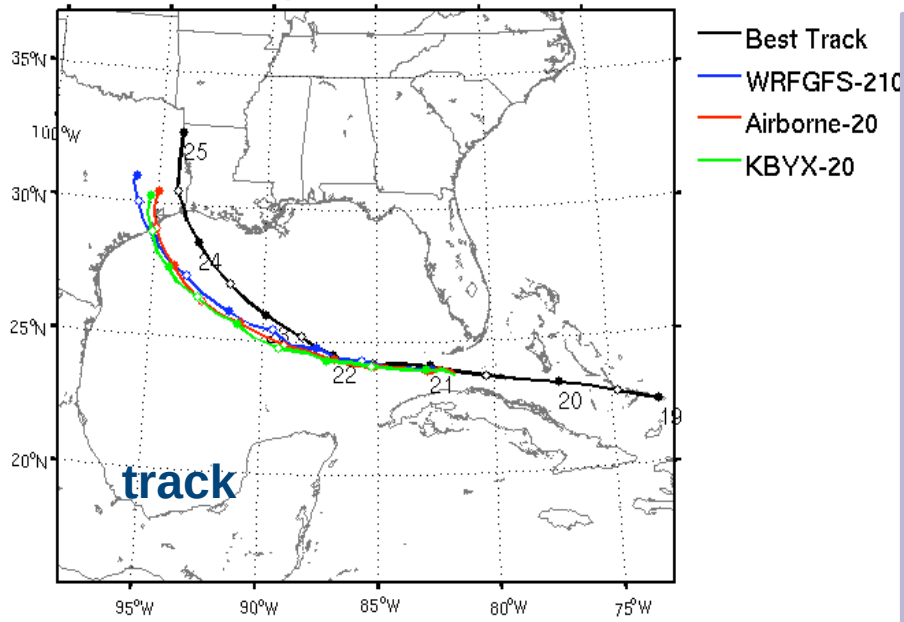


1.5° SOs

Forecasts from EnKF with Airborne vs. NEXRAD





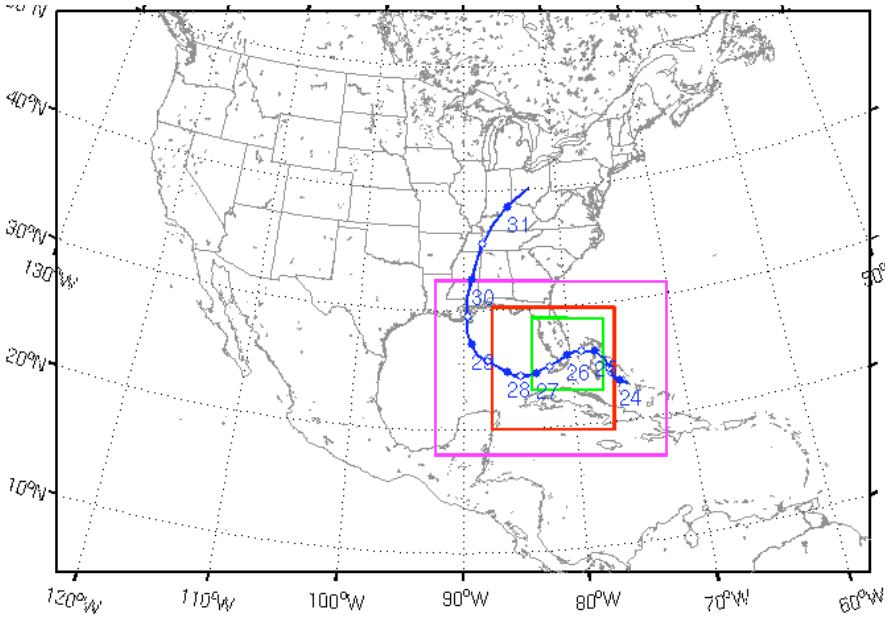


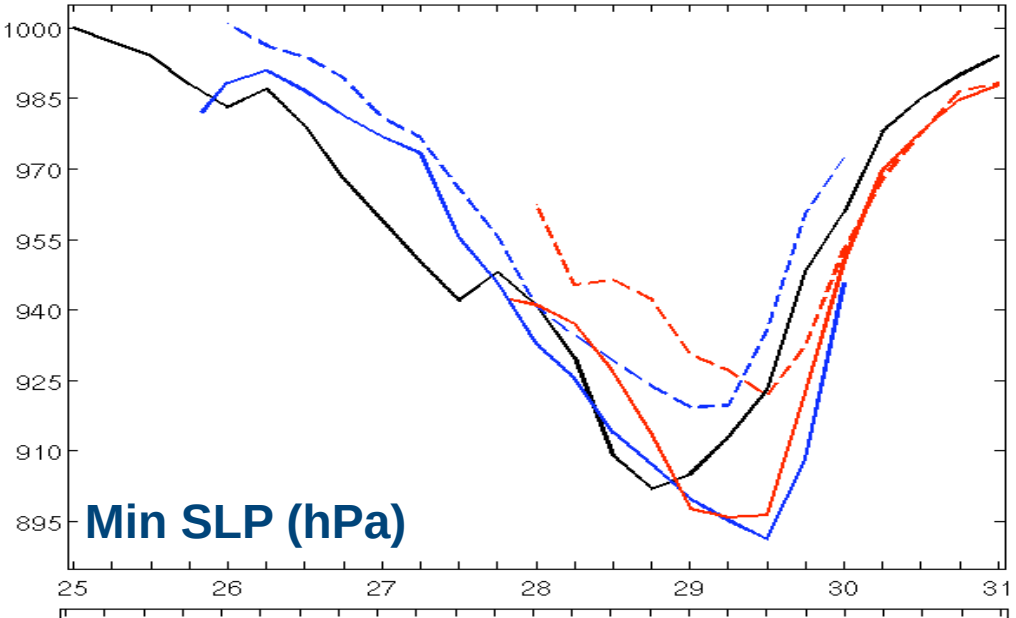
WRFGFS-2100: WRF deterministic forecast took GFS 0000UTC Sep21 analysis as IC and its forecast as BC;

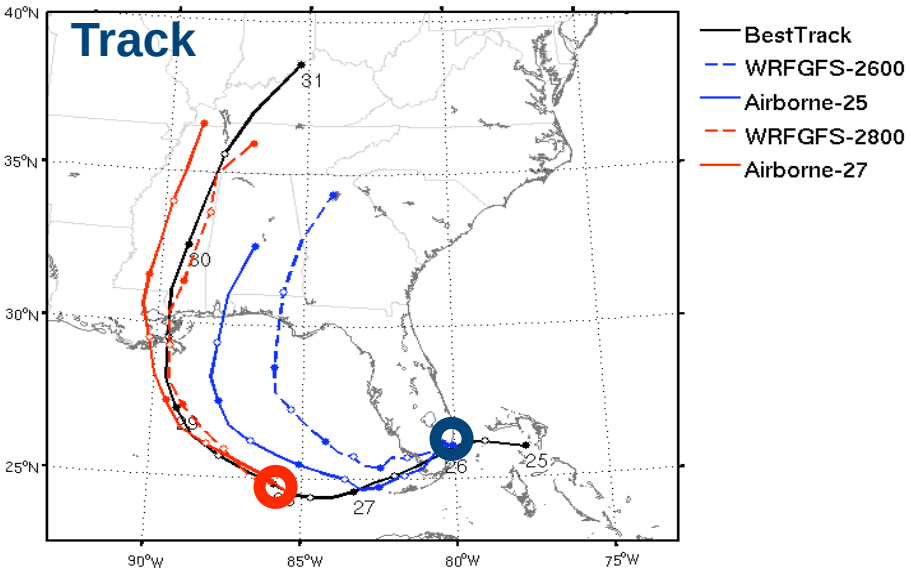
Airborne-20: WRF DF from the EnKF analysis at 1800UTC Sep20 which assimilated N43 Vr at 1600, 1730 and 1800UTC Sep20;

KBYX-20: WRF DF from the EnKF analysis at 1800UTC Sep20 which assimilated KBYX Vr at 1600, 1700 and 1800Z Sep20.

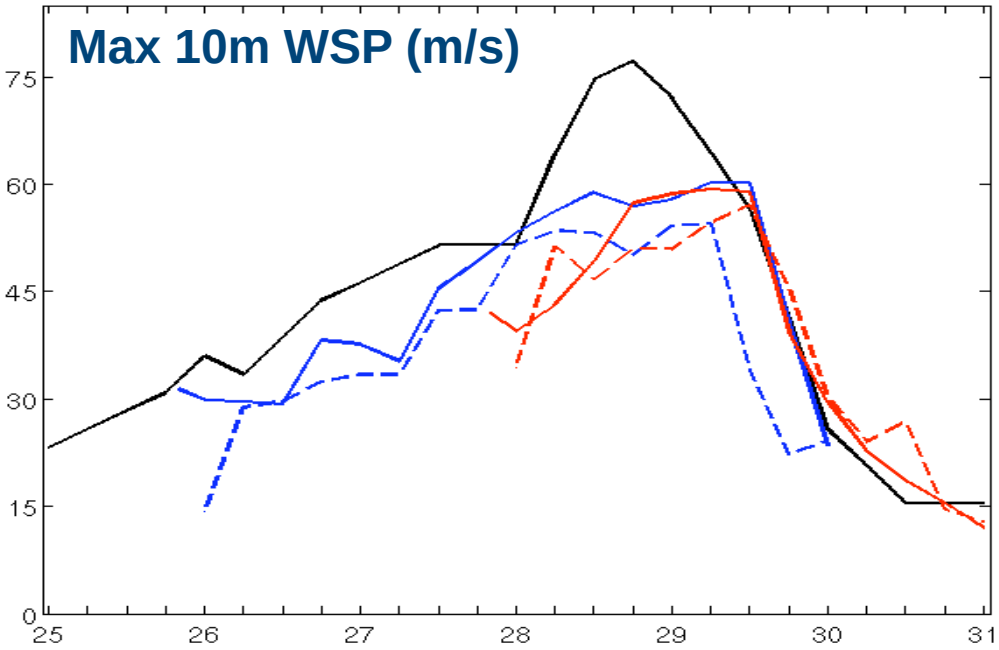
Impacts of Airborne Vr EnKF for Katrina (2005)



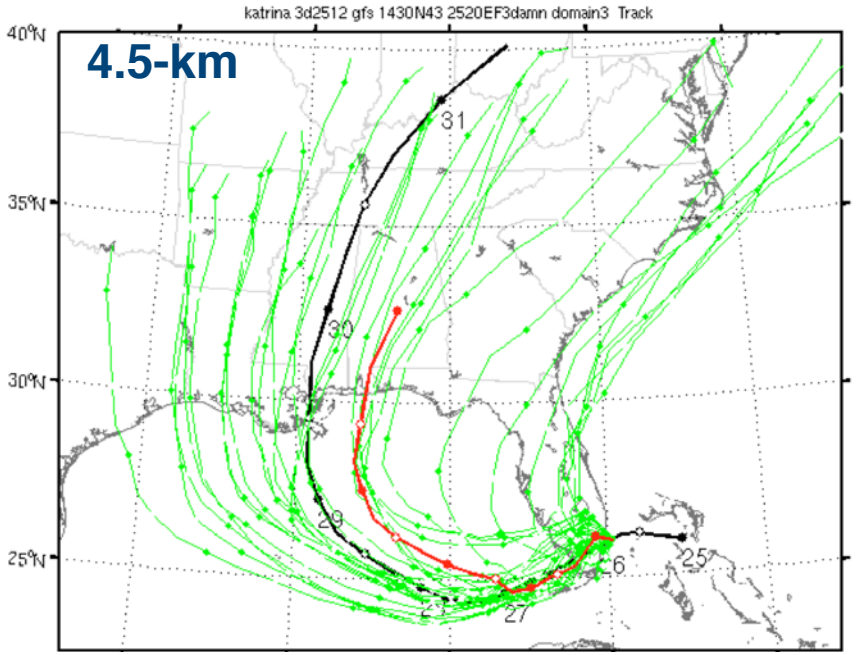


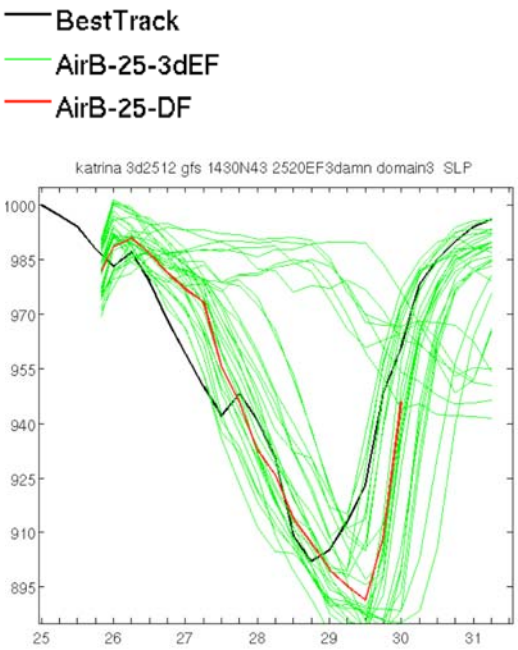


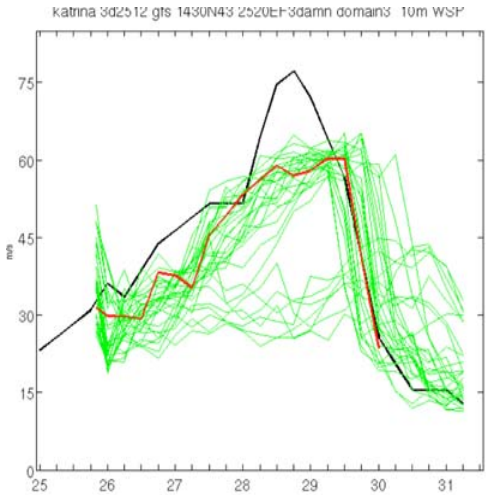
BestTrack
WRFGFS-2600
Airborne-25
WRFGFS-2800
Airborne-27

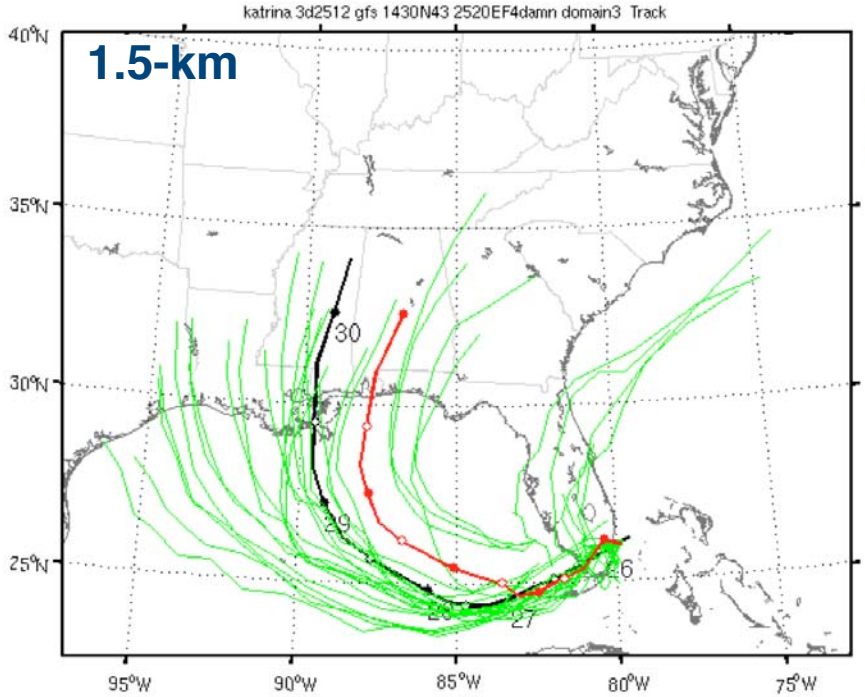


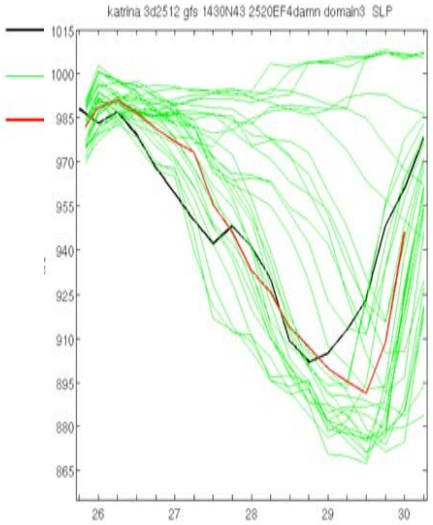
4.5-km (top, 126h) vs. 1.5-km (bottom, 102h) ensemble fcsts

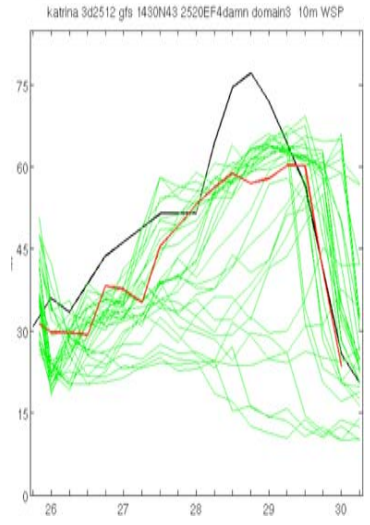








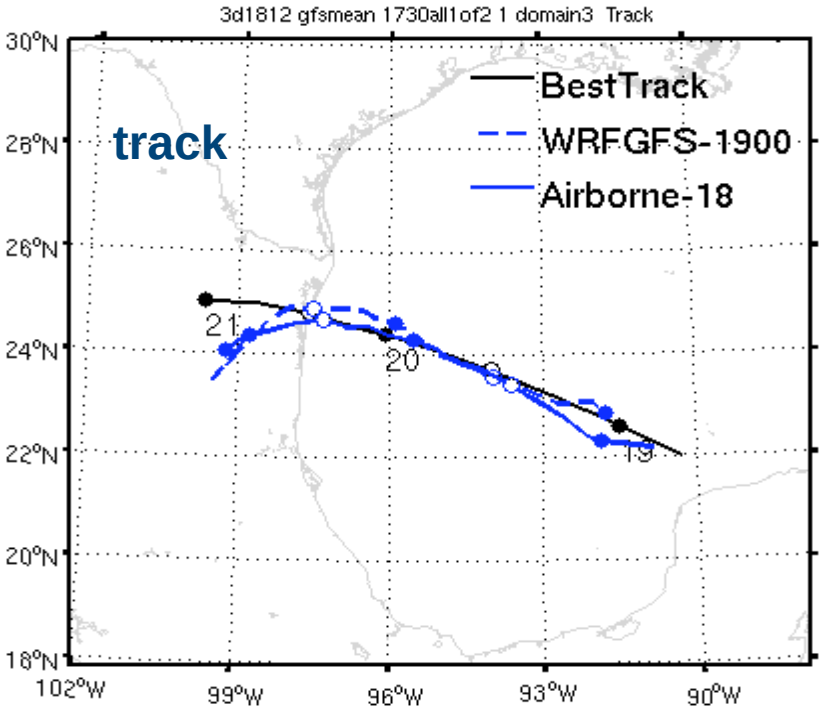


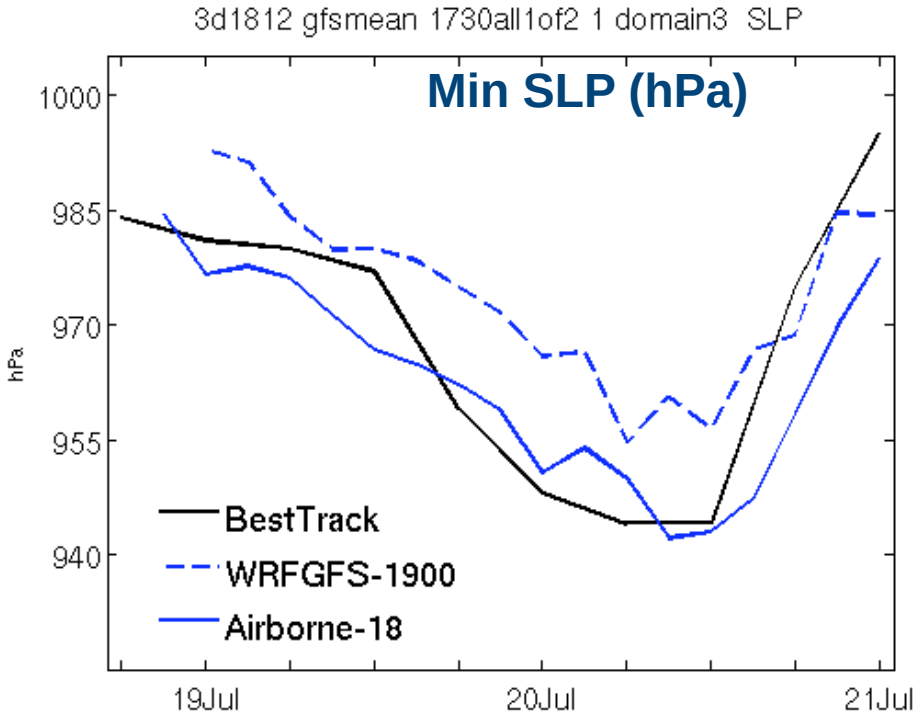


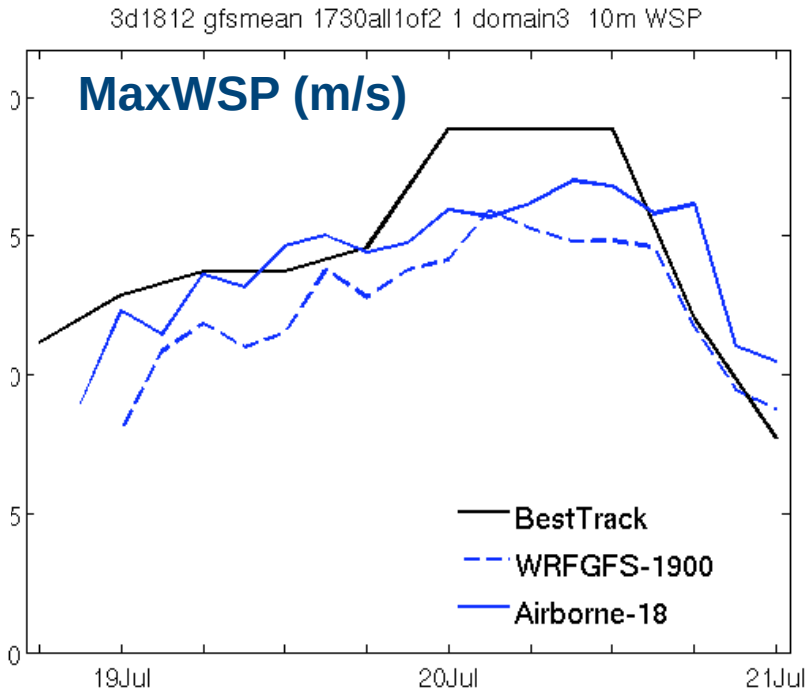
MinSLP

MaxWSP

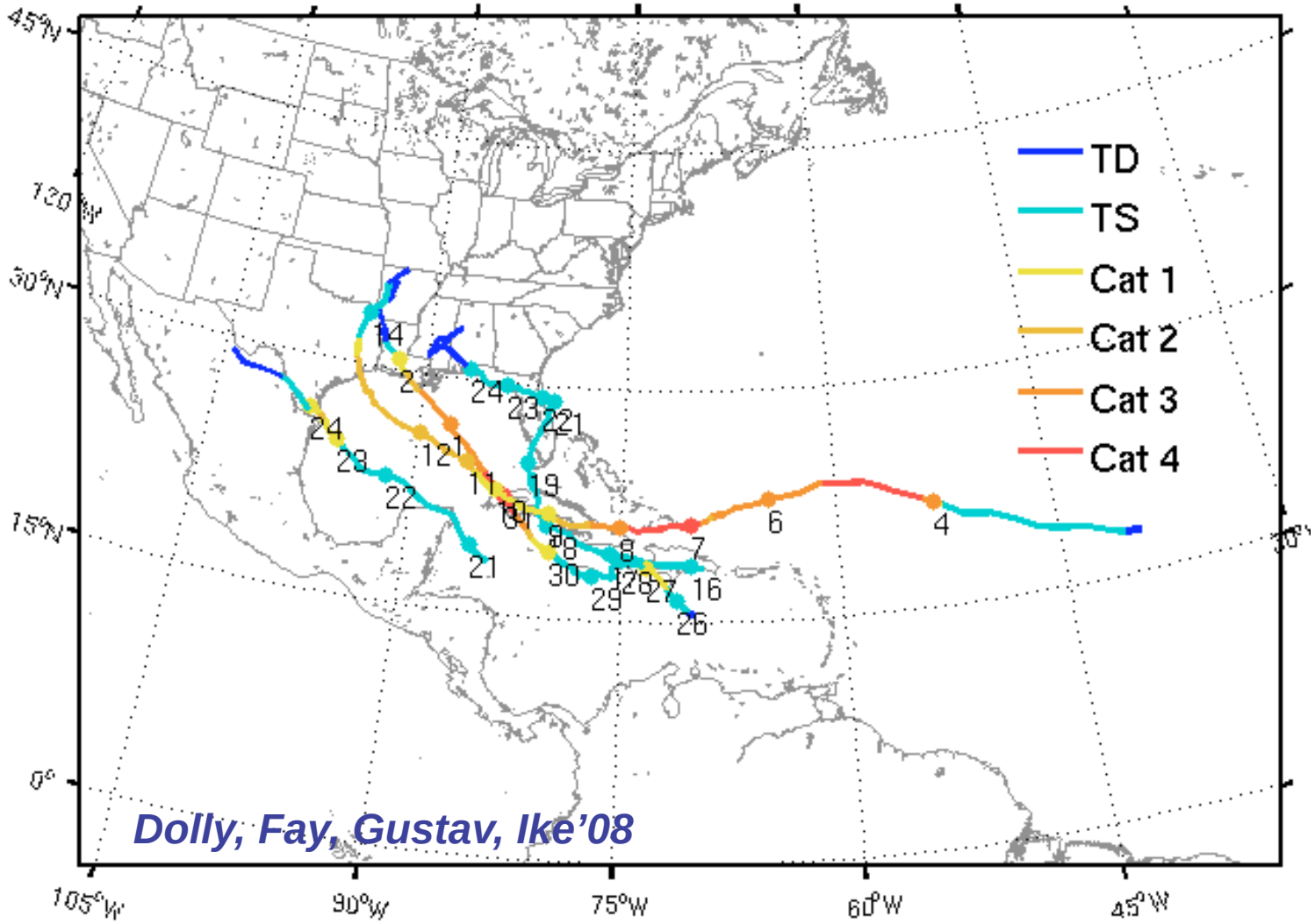
Hurricane Emily (2005): WRF/ARW Forecasts from GFS vs. EnKF







TOWARDS REALTIME ASSIMILATION OF DOPPLER RADAR OBSERVATIONS FOR CLOUD -RESOLVING HURRICANE PREDICTION



Thanks to John Gamache, our Vr superobbing procedure is now implemented on P3 in realtime

NOAA HFIP Use of TACC Computing

GOAL:

1. **Make progress on establishing operational value of higher resolution modeling (global and hurricane, including ensembles) to improving forecast performance.**

2. **Demonstrate potential of on-demand computing to hurricane forecast operations.**

3. **Inform future R&D needs for HFIP goals and objectives toward the development and implementation of next-generation HFS.**

4. **Focus research to provide tangible benefit within 3 - 5 years.**

System Name:	**Ranger**
Operating System:	**Linux**
Number of Cores:	**62,976**
Total Memory:	**123TB**
Peak Performance:	**579.4TFlops**
Total Disk:	**1.73PB (shared)**
NOAA Allocation :	**30M SUs (until 1 Jan 2009)**

PI for the allocation: Frank Marks

PENNSTATE 1855 | TEXAS A&M UNIVERSITY | TACC TEXAS ADVANCED COMPUTING CENTER *Powering Discoveries That Change The World* | THE UNIVERSITY OF TEXAS AT AUSTIN | NOAA NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION U.S. DEPARTMENT OF COMMERCE

HFIP-TACC On-demand Test

- Diverse NOAA (HRD, ESRL, NCEP/NHC, NCO, EMC) and university (PSU, TAMU, TACC) team established on-demand capability to support operational hurricane forecasting.
- Built upon HFIP high-resolution test plan to use high resolution global (FIM at 15-km) and regional (ARW at 1.5-km using EnKF to assimilate Doppler radar superobs) models to demonstrate on-demand capability.
- NCEP model fields and Doppler radar superobs from NOAA P-3 aircraft flow automatically to TACC, research models run, output products generated for forecasters, and products transferred to NHC via NCO.
- Portions of process tested during Dolly and Fay, with a test of complete system during Gustav and Ike.

Towards Real-time Assimilation of Airborne Radar Observations with EnKF: Same *Experimental Design as Test Cases*

WRF/ARW triply-nested domains for both EnKF analyses and free forecasts:

D1: 121x160x40.5km x 35 levels (similar to GFDL coarse domain)

D2: 121x160x13.5km x 35 levels

D3: 253x253x 4.5km x 35 levels (moving nest in forecast mode)

Time performance of standard real-time WRF/ARW forecast initialized with GFS

Waiting time for GFS completion: 4.5 h

Transfer GFS analysis and forecasts from NCEP to TACC: 0.3 h

Initialization of WRF/ARW with GFS using WPS: 0.4 h

126-h WRF free forecast with 512 processors: 2.7 h

Total time lapse: 7.9 h (3.4 h after GFS completion, 1.5 km is 7 h after)

Estimated real-time WRF/ARW forecast initialized assimilating airborne Vr data

EnKF ensemble initialized with most recent available GFS: no waiting time

Quality control and super-observation (SO) of Airborne data per hour: 0.3h

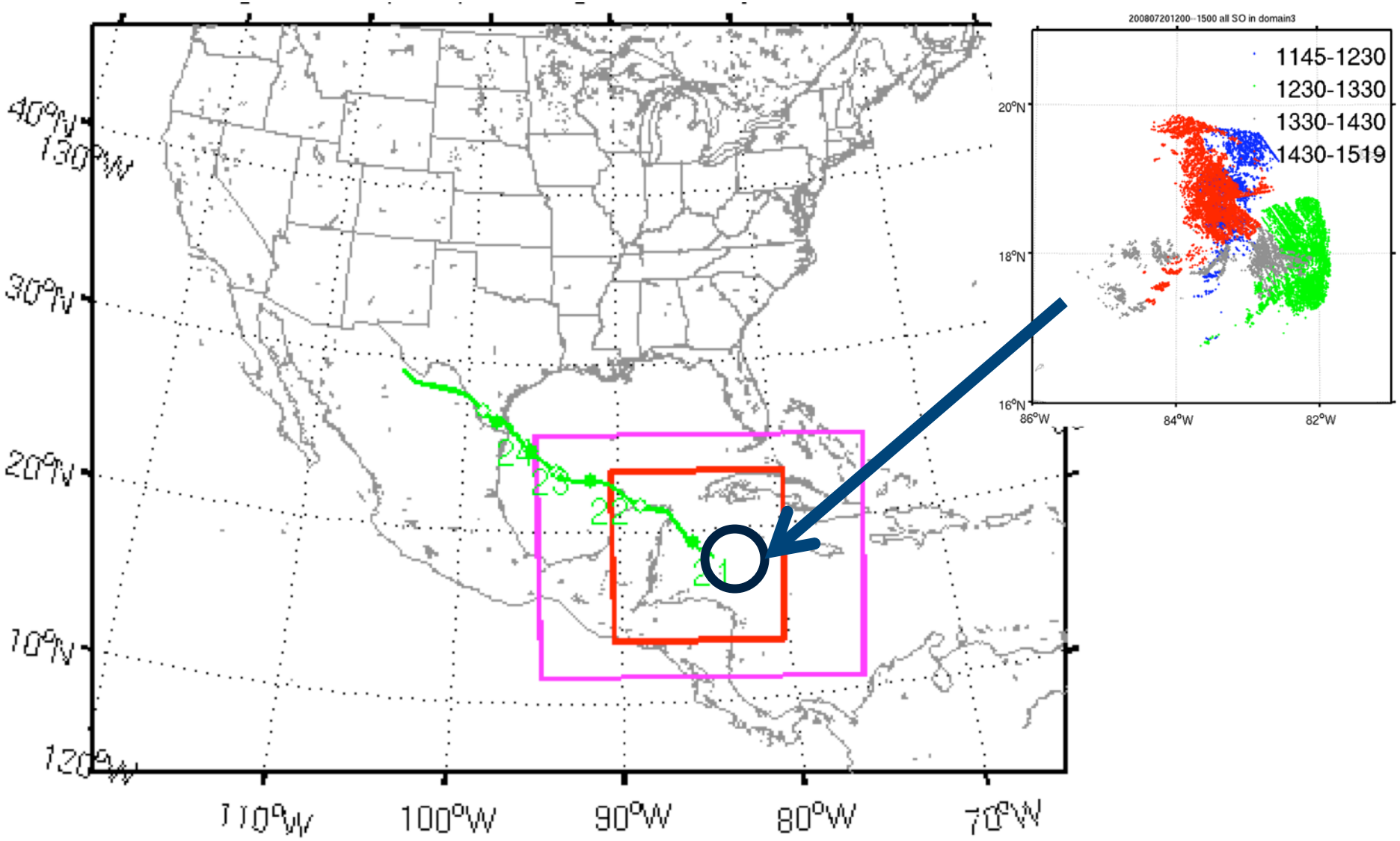
Transfer airborne ~3000 SOs from P3 to TACC: 0.2 h

EnKF assimilation of 1-h SOs: 0.5 h

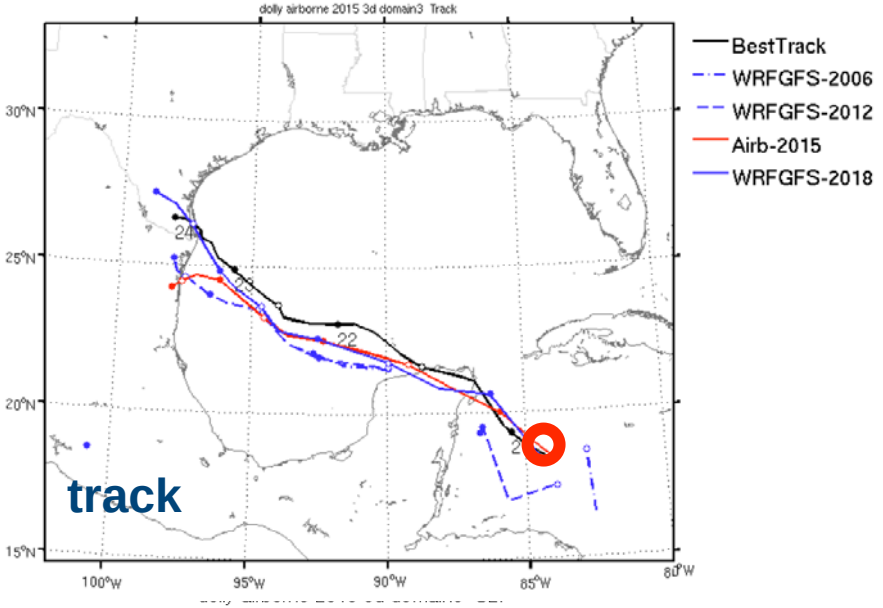
126-h WRF free forecast with 512 processors: 2.7 h

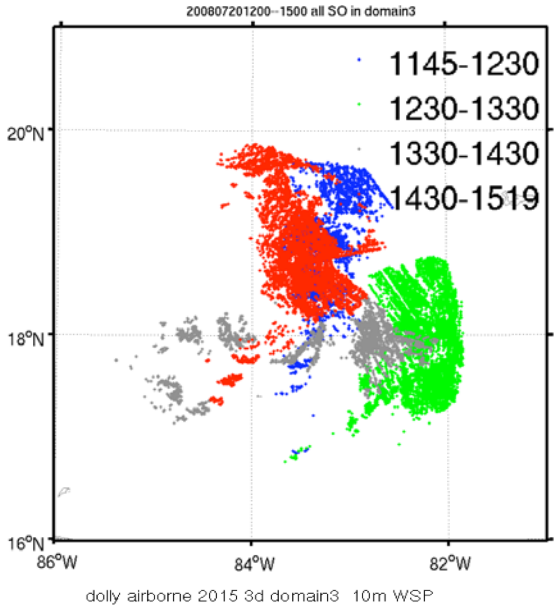
Total time lapse: 3.7 h (1.5-km is 7 h) after Doppler observations taken

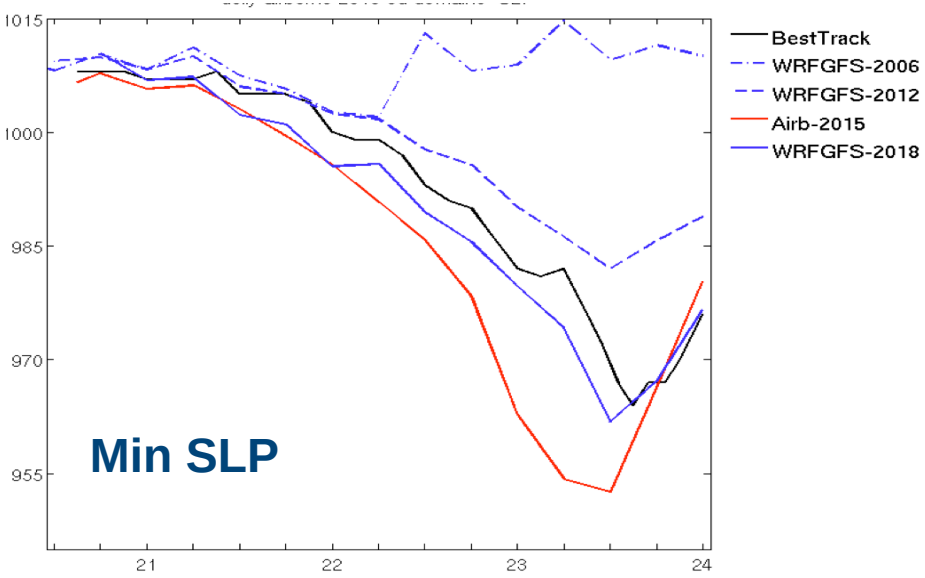
Near-realtime Tests of Hurricane Dolly (2008)
SOs Generated shortly after P3 mission

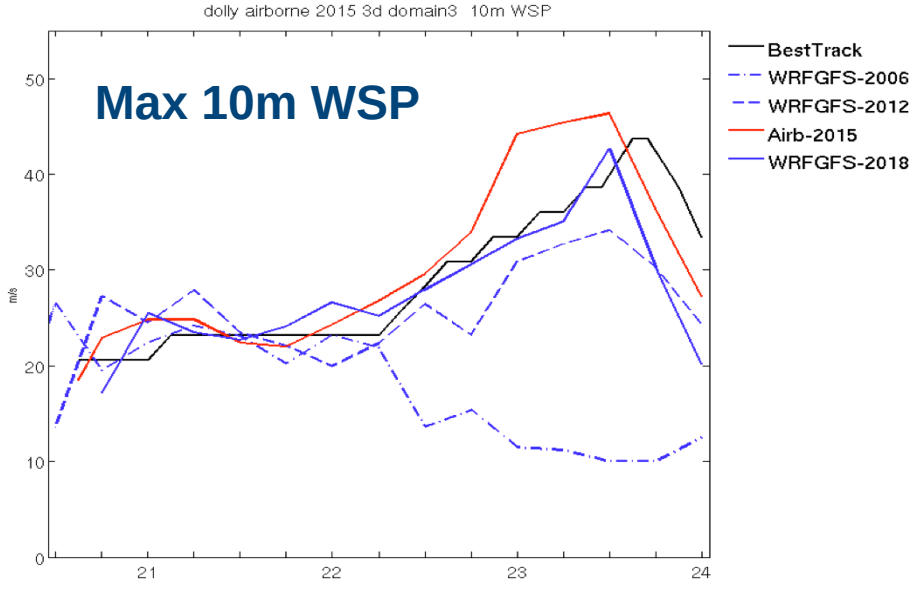


Performance of Airborne Vr Assimilation for Dolly (2008)



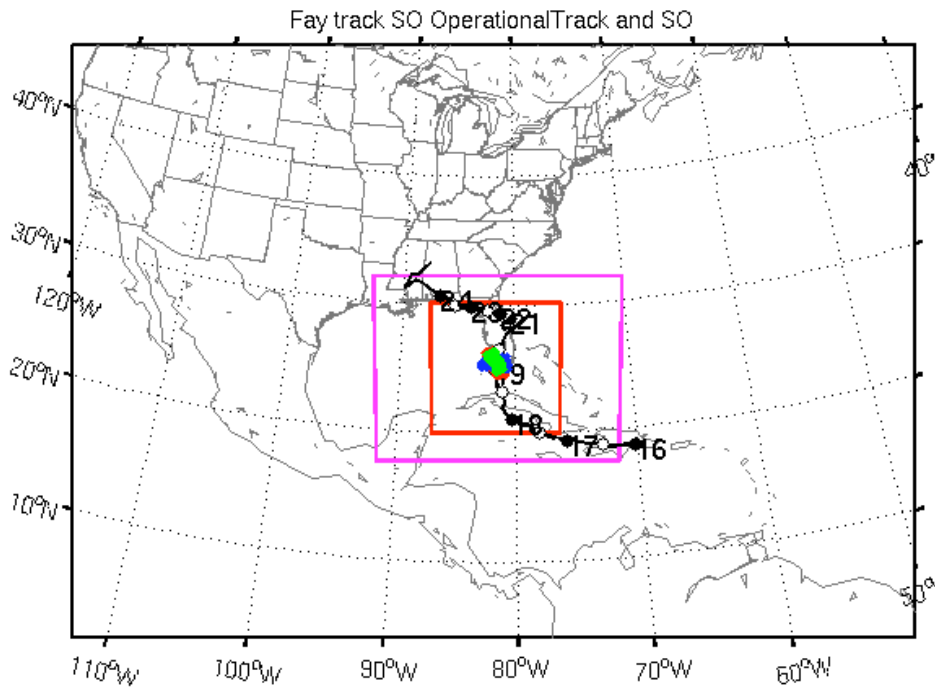


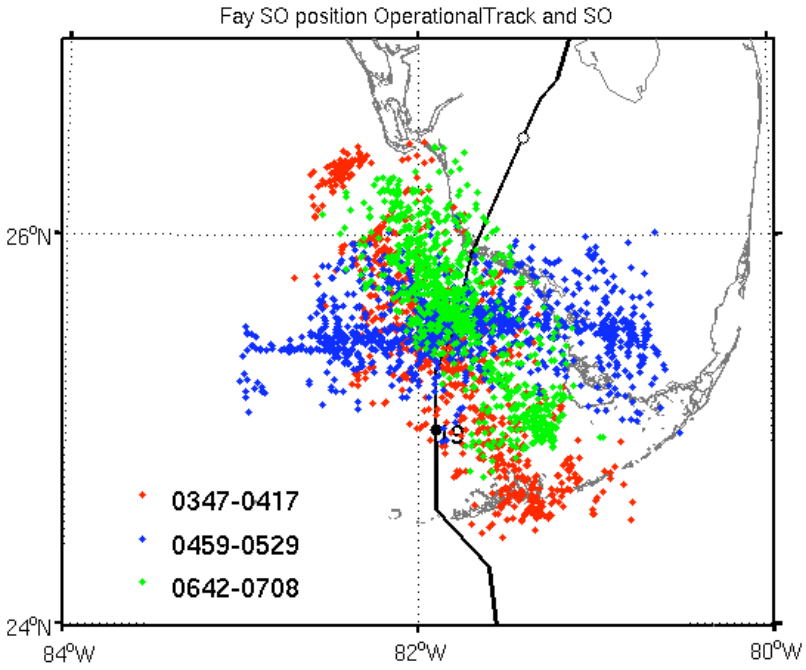




Near-realtime Tests of Hurricane Fay (2008)

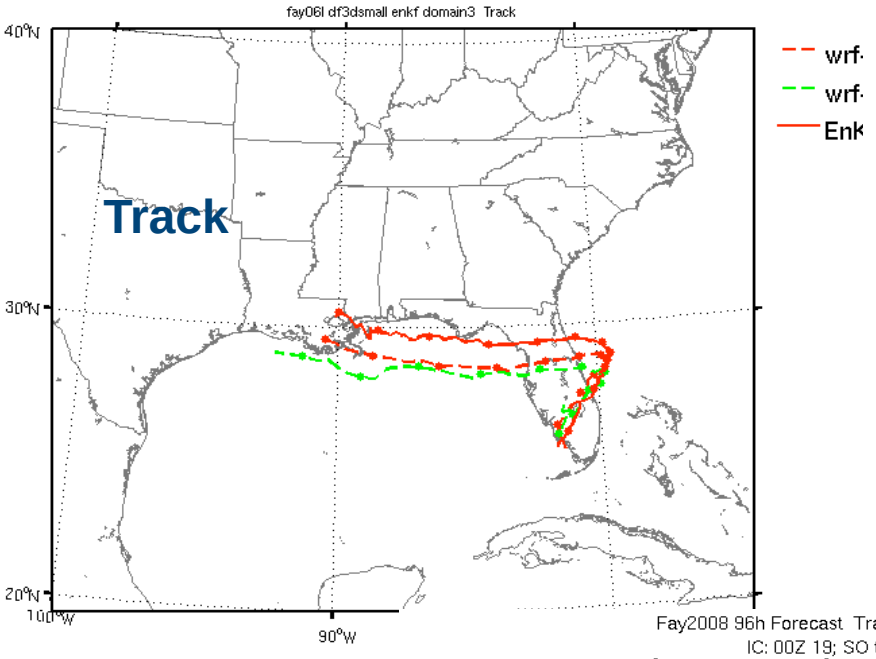
SOs Generated during P3 mission and are assimilated a few hours later

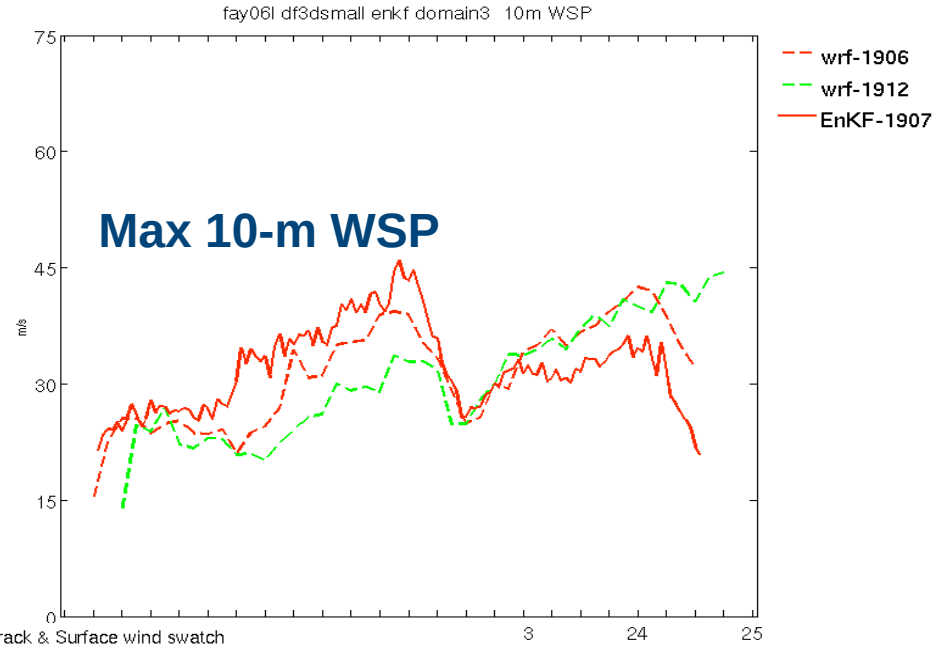


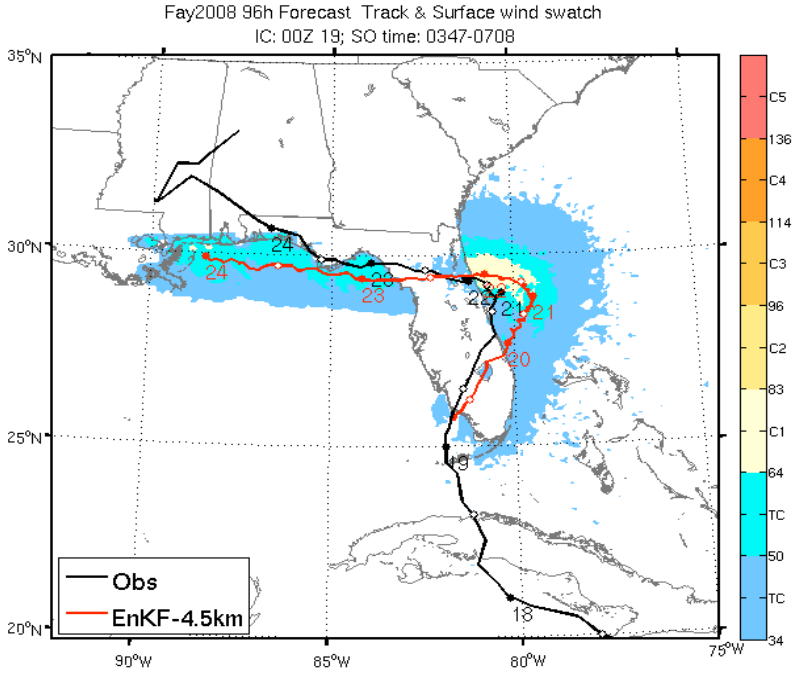


ARW from GFS at 00Z/19; Vr SOs during 3-07Z/19

Impact of Airborne Vr OBS for Fay

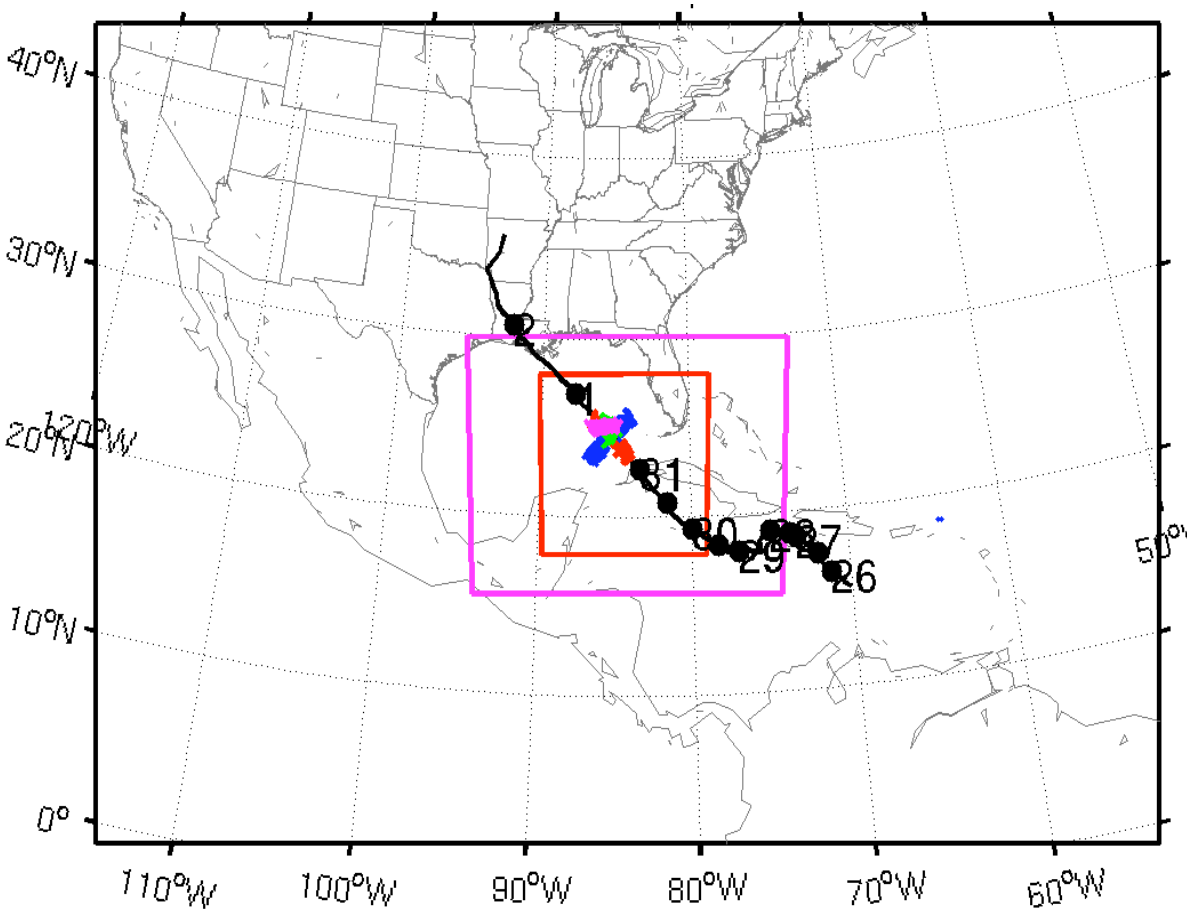


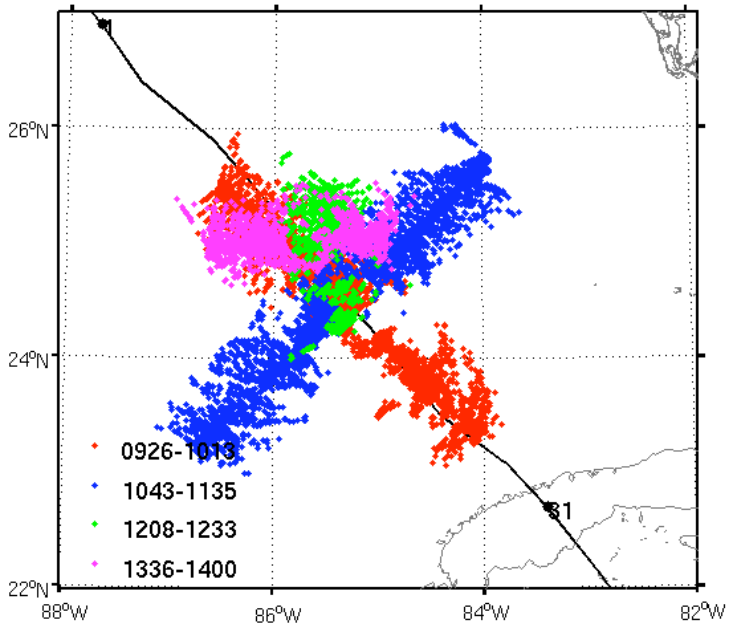




Realtime Tests of Hurricane Gustav (2008)

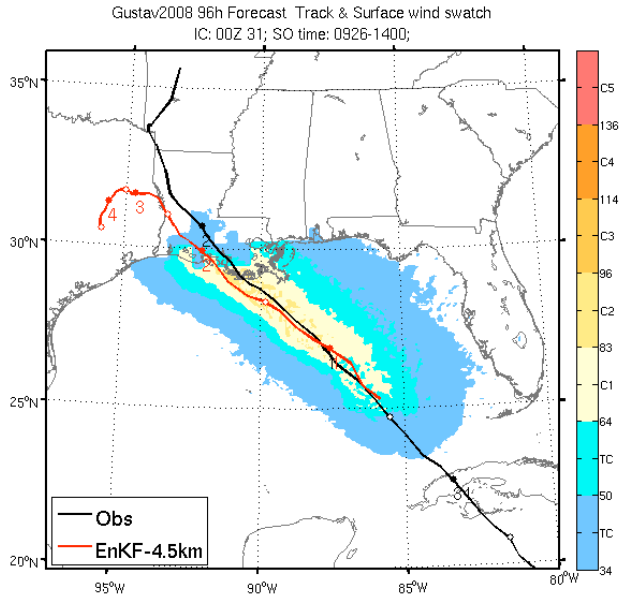
SOs Generated/assimilated during P3 mission

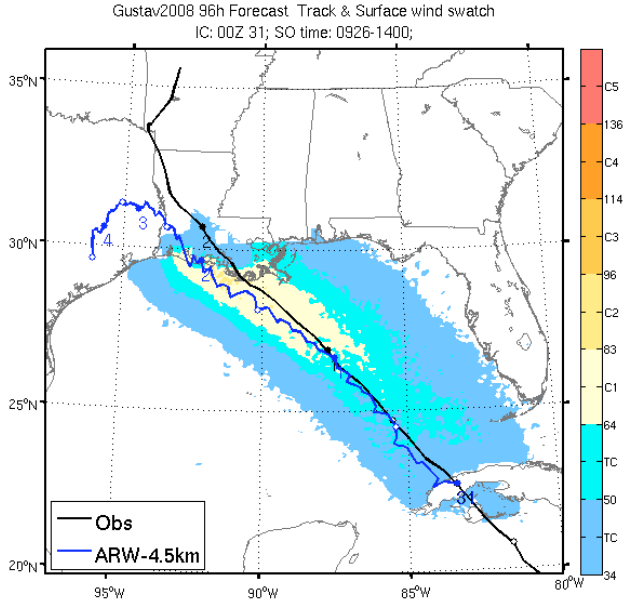


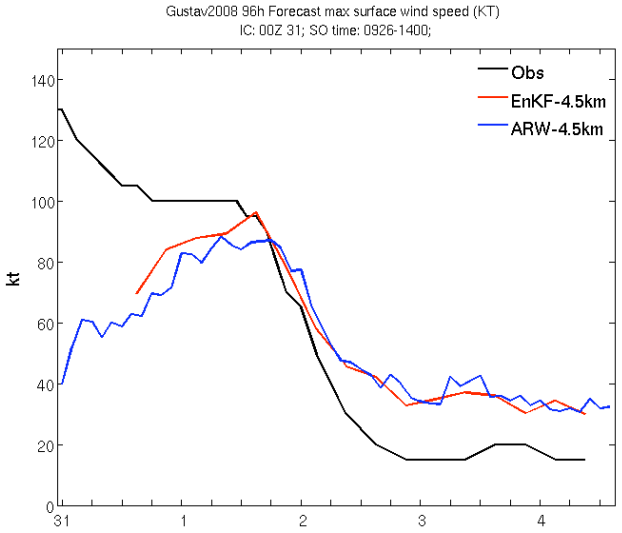


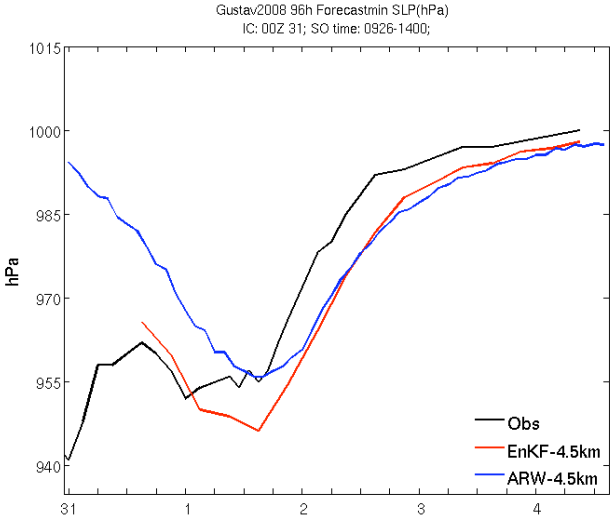
ARW from GFS at 00Z/31; Vr SOs during 9-14Z/31

Impact of Airborne Vr for Gustav



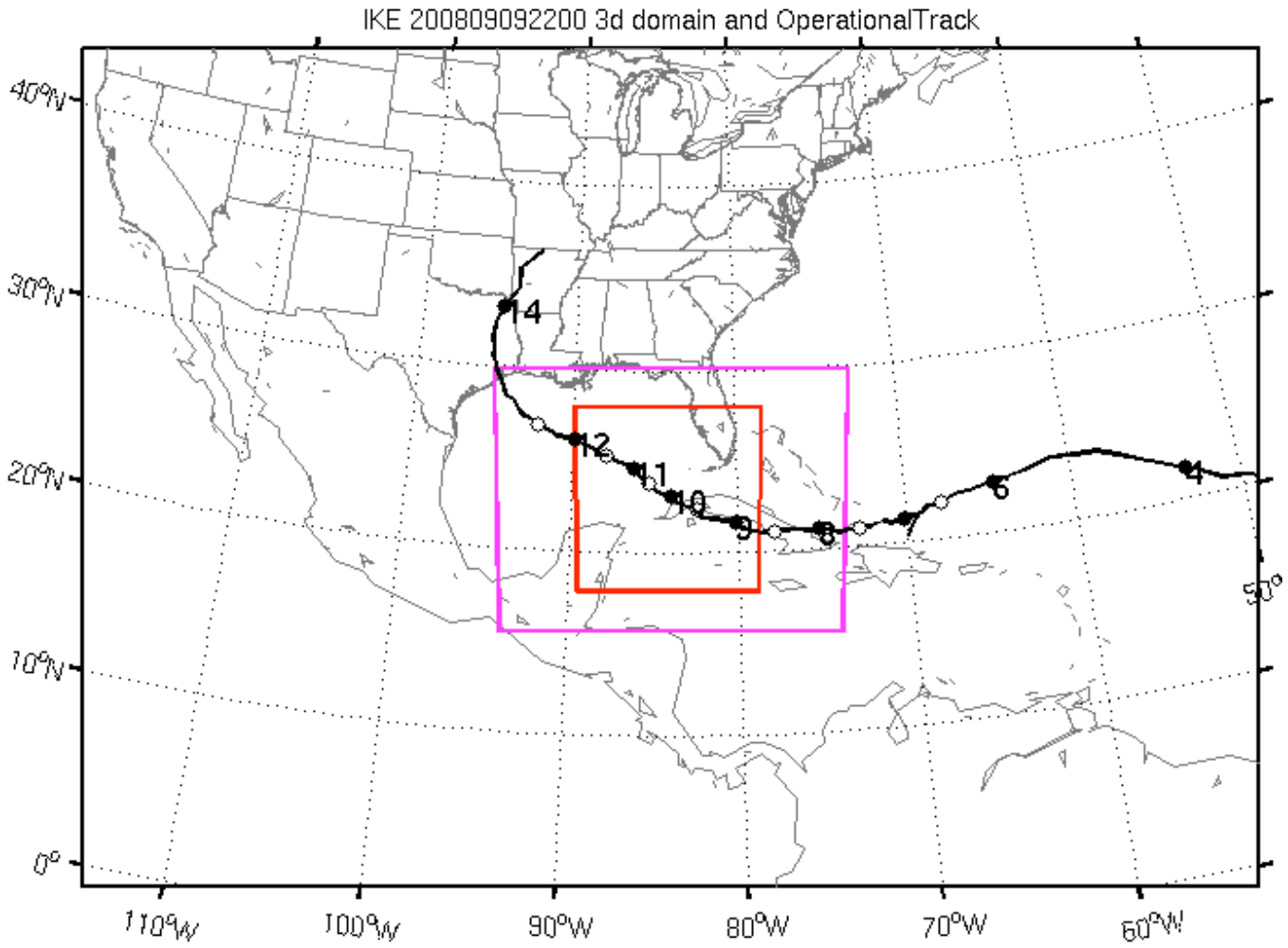






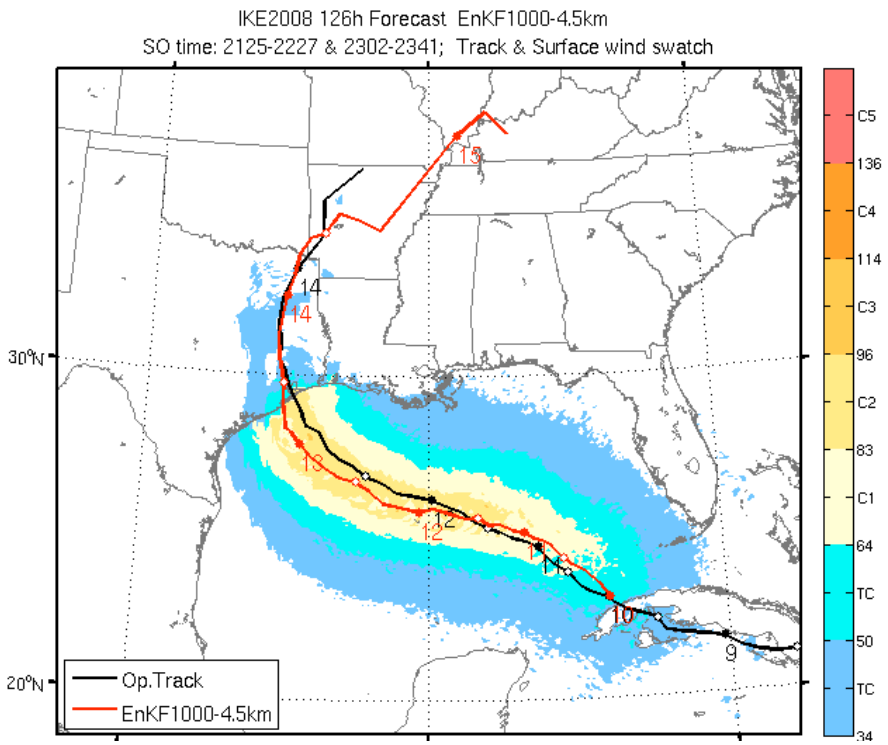
Realtime Tests of Hurricane Ike (2008)

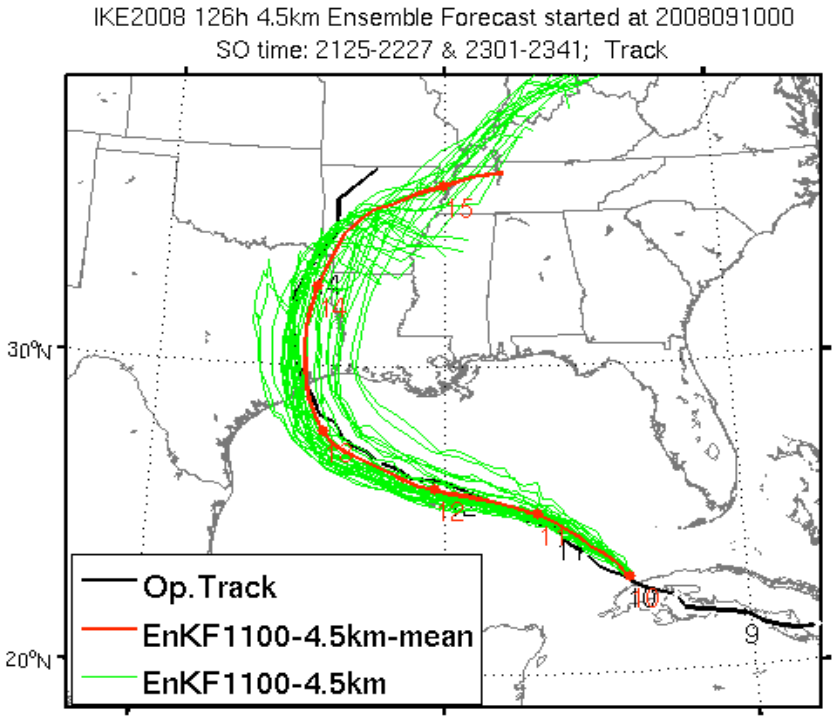
SOs Generated/assimilated during P3 mission

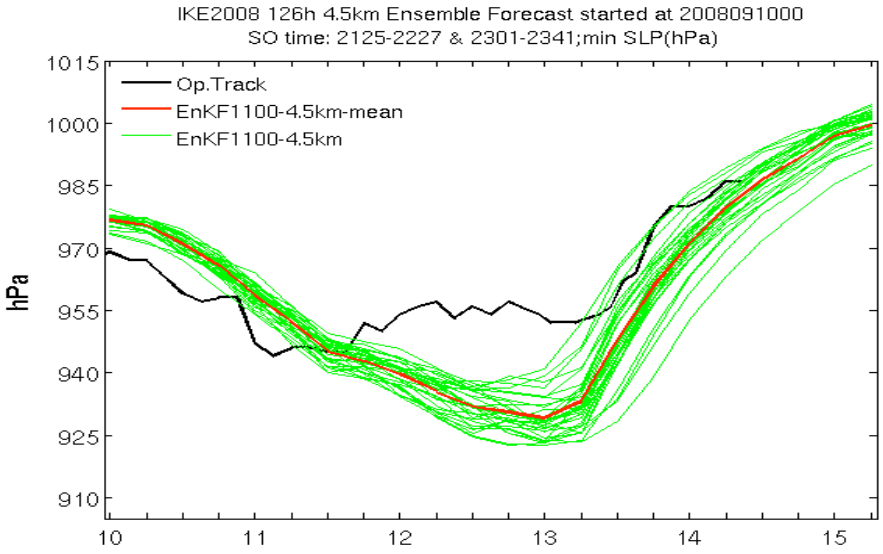


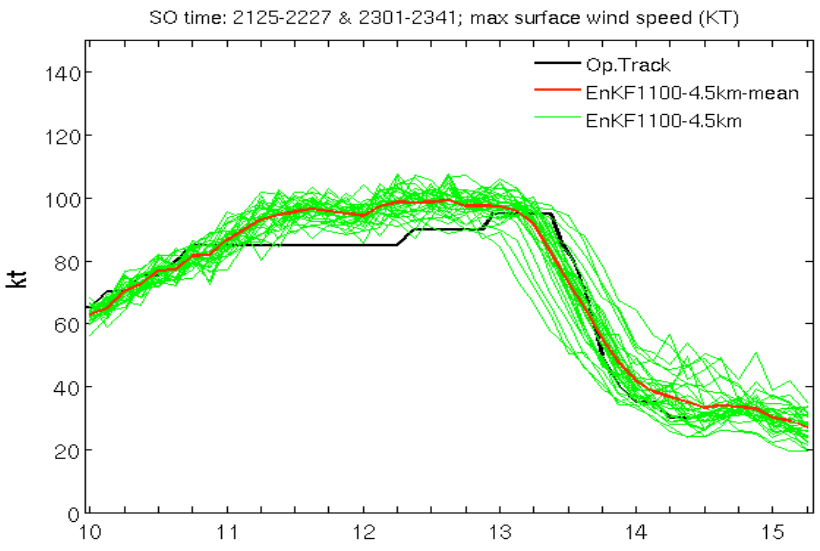
ARW from GFS at 12Z/9; Vr SOs during 21-24Z/09

Realtime ARW Performance with Vr EnKF

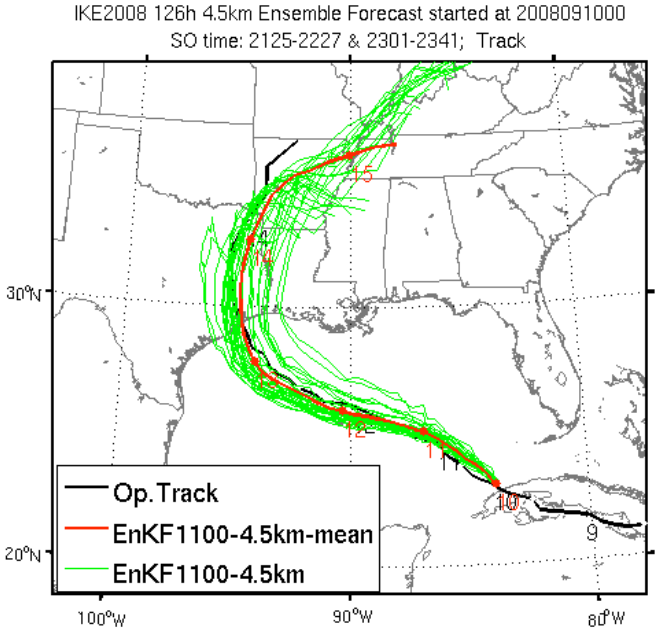


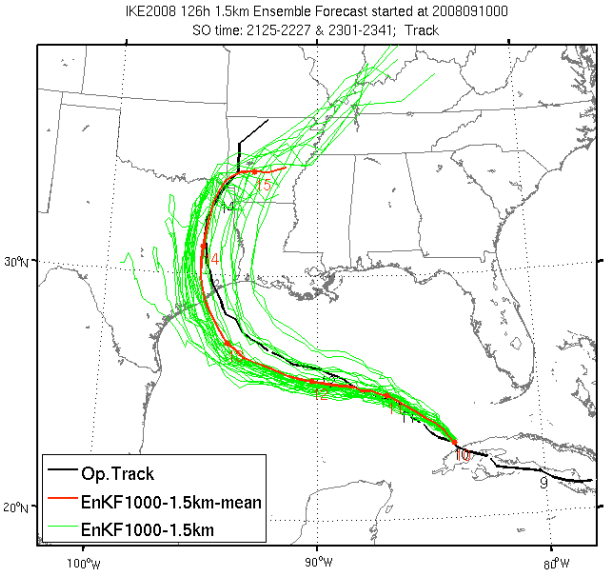




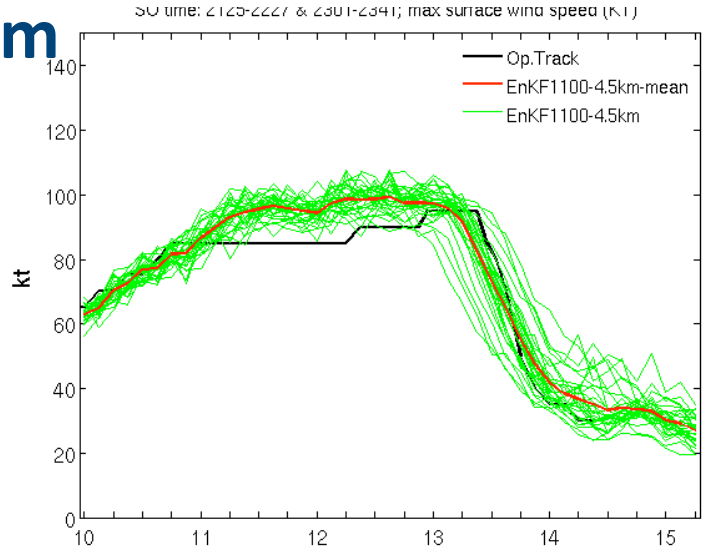


Realtime: Ensemble Sensitivity to Resolution

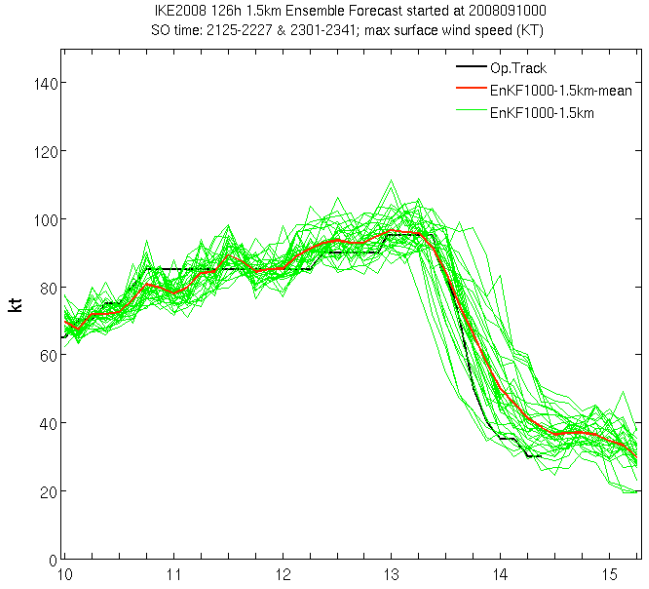




4.5km



1.5km



Concluding Remarks

- EnKF assimilation with both the ground-based and airborne radar observations into cloud-resolving mesoscale models is promising for initializing hurricanes near observed intensity and for subsequent forecast
- The impacts of airborne Vr are similar to WSR-88D Vr
- EnKF combines data assimilation and ensemble forecast that provides flow-dependent analysis/forecast uncertainty
- Real-time, on-demand, convective-resolving ensemble analysis and forecast experiments on NSF HPC facility assimilating airborne Doppler observations shows great promises for the future of hurricane prediction
- WRF/ARW forecasts are surprisingly similar for the 4.5-km and 1.5-km grid spacings; 4.5-km grid very practical

Experimental Design Using EnKF to Assimilate Airborne Radar Observations: *Towards Potential Real-time Applications*